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CHEMICAL TECHNOLOGY AND ECONOMICS IN ENVIRONMENTAL PERSPECTIVES. TASK III. CHLOROFLUOROCARBON EMISSION CONTROL IN SELECTED END-USE APPLICATIONS

MIDWEST RESEARCH INSTITUTE
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PREPARED FOR
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CHEMICAL TECHNOLOGY AND ECONOMICS IN ENVIRONMENTAL PERSPECTIVES

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16. ABSTRACT

The purpose of this study was to identify the potential sources of emission for three of the major end-use applications of F-11, -12, -13, -113, and -114 and to identify current and potential methods for controlling emissions from these sources. For identified methods of control, the efficiency of the method and the economics of its application were determined. In applicable areas, the feasibility, cost, and effectiveness of new or modified operating and/or maintenance procedures were studied as a means of reducing emissions. The areas of study were refrigeration and air conditioning, plastic foam blowing agents, and cleaning and drying applications. This study did not include an assessment of the risks associated with the environmental discharge of these chemicals. Actual and potential sources of chlorofluorocarbon emission were identified in each of the three areas. Known methods of emission reduction, efficiencies, and economics are discussed for the fields of refrigeration and air conditioning and for solvent and drying applications. Proposed methods were delineated for the plastic foam blowing agent field.

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Task III - Chlorofluorocarbon Emission Control in Selected End-Use Applications

Contract No. 68-01-3201

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PREFACE

This report presents the results of Task III, "Chlorofluorocarbon Emission Control in Selected End-Use Applications," of a project entitled "Chemical Technology and Economics in Environmental Perspectives." The project is being performed by Midwest Research Institute under Contract No. 68-01-3201 for the Office of Toxic Substances of the U.S. Environmental Protection Agency. Dr. Irving J. Gruntfest is the project officer. This program has MRI Project No. 4101-L.

Dr. Thomas W. Lapp is the project leader for this contract. Particular credits for authorship or partial authorship of portions of this report include the following: Dr. Lapp, Chapters I, III, and V; Mr. Thomas Weast, Chapter III; Dr. Ralph Wilkinson, Chapter III; and Mr. Howard Gadberry, Chapter IV. All authors contributed to Chapter II. Mr. Burl Kinder provided technical assistance for the area of refrigeration and air conditioning. This program is under the supervision of Dr. Edward W. Lawless, Head, Technology Assessment Section, Environmental and Materials Sciences Division.

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Approved for:

MIDWEST RESEARCH INSTITUTE

L. J. Shannon

L. J. Shannon, Director
Environmental and Materials
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November 30, 1976

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SECTION I

INTRODUCTION

The technical controversy over whether certain chlorofluorocarbons are destroying the earth's protective ozone shield has evolved into a public issue. Legislation is being considered at both the state and federal levels to limit or ban the use of certain of these materials. While many technical questions remain to be answered, responsible public officials and regulatory agencies are trying to determine the technical and economic feasibility of using alternative chemicals, of substituting mechanical devices, and of reducing emissions from selected end-use applications. In addition, they seek to identify the social consequences resulting from the regulation of the various uses of these materials.

It should also be noted that not all chlorofluorocarbons or fluorocarbons are considered to be equally detrimental to the ozone layer nor are these compounds the only halogenated species in the upper atmosphere. The five halocarbons covered in this report are those of commercial significance that may be damaging to the ozone layer. Other commercially available chlorofluorocarbons are, at this time, considered to be less hazardous to the ozone layer.

Midwest Research Institute (MRI) recently published a report on the evaluation of feasible chemical alternatives to selected chlorofluorocarbon uses.1/ Other studies on chlorofluorocarbons have dealt with stratospheric effects, biological effects of ozone reduction, human health effects, and a review of the "fluorocarbon industry."2/ A study conducted by Syracuse University Research Corporation offered an appraisal of environmental hazards of one and two carbon fluorocarbons.3/ Another major study was a preliminary impact-assessment of possible regulatory actions to control atmospheric emission of selected halocarbons.4/ Numerous governmental reports have been published on the economic and energy impacts of complete chlorofluorocarbon regulation.

The objective of this study was to document the sources of emission of F-11, F-12, F-13, F-113, and F-114 within the use areas of refrigeration and air conditioning, the foam-blowing industry, and cleaning and drying solvents. For each source of emission, feasible emission control procedures or equipment were to be identified, with an evaluation of the effectiveness or efficiency of control and the cost for each suggested control method.

This study was not directly concerned with the current ozone depletion hypothesis or the environmental ramifications of that hypothesis. No judgement on that question should be inferred from any of the results of this study.

The three areas of application stated above account for approximately 40% of the total consumption in 1975 of these five chlorofluorocarbons. In terms of specific areas, the refrigeration and air conditioning industry consumes the largest percentage (28%), followed by the foam-blowing applications (7%). Cleaning and drying applications consume the lowest percentage (5%) of these three areas.[5] MRI has worked closely with industry in this evaluation of the sources of chlorofluorocarbon emission and the possible methods for controlling these emissions. It is conceivable that some of these methods could be employed and emissions reduced to a level such that a ban on the use of selected chlorofluorocarbons may not be necessary in certain use areas. Industry, however, must be willing to acknowledge the deficiencies and poor practices that exist and strive to correct their problems.

Throughout the literature and in discussions with personnel directly involved with the industry, several different designation systems are widely used for the halocarbons. In all industries, other than refrigeration, the halocarbons are given an F prefix (fluorocarbon) while in the refrigeration industry the compounds have an R prefix (refrigerant). Thus, F-12 and R-12 are the same compound, only the prefix is different and reflects the custom of different industries.

This document is intended to be useful to policy makers and the public in understanding the feasibility, effectiveness and cost of controlling emissions of the five chlorofluorocarbons during their use in the three areas of application. It is organized in a manner which we feel will provide the greatest utility to the reader. The next section summarizes the findings of this study with respect to the control of emissions from each of the three use areas. Sections III through V present a detailed discussion of the technical considerations to be applied to emission control in the areas of refrigeration and air conditioning, foam-blowing applications, and degreasing and dry cleaning solvents. For each of these areas, the sources of emission are identified and feasible methods of emission control are shown but no attempt has been made to select the single most attractive method or to provide any rank-order of the methods.

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SECTION II

SUMMARY AND CONCLUSIONS

Evidence that chlorofluorocarbons may be detrimental to the earth's ozone layer was first reported about 2.5 years ago. Since that time, numerous experimental and theoretical studies have been made on the effect of specific chlorofluorocarbons on ozone. Studies have also been conducted to identify substitute chemical and alternative methods for delivering goods and services now provided by chlorofluorocarbons and to determine the economic and commercial ramifications which would occur if the uses of these chemicals are regulated.

Earlier studies of the possible economic and commercial impacts are exemplified by the topical areas of a preliminary economic impact assessment of possible regulatory actions, governmental assessments of the economic and employment impacts of possible regulatory actions, and a study of alternatives to selected current chlorofluorocarbon use applications. These studies have been referenced in this and earlier reports.

The purpose of this study was to identify the potential sources of chlorofluorocarbon emission for three of the major end-use applications of F-11, -12, -13, -113, and -114, and to identify current and potential methods by which the emissions from these sources can be controlled. For identified methods of emission control, the efficiency of the method and the economics of its application were to be determined. In applicable areas, the feasibility, cost, and effectiveness of new or modified operating and/or maintenance procedures were to be studied. The three areas chosen for study were (1) refrigeration and air conditioning; (2) foam blowing applications; and (3) cleaning and drying applications. These areas appear to present the greatest potential for possible emission control. The lack of technically and economically feasible substitutes for these use categories suggests that control of emission is one alternative that merits serious consideration. This study considers the technical and economic feasibility of emission control strategies for each of these uses.

The results of this study can be summarized as follows for each use category.

REFRIGERATION AND AIR CONDITIONING

Within this broad area, four specific kinds of equipment and uses were chosen for study: (1) home refrigerators and freezers; (2) mobile air conditioners; (3) commercial chillers; and (4) food and beverage refrigerators. These four specific uses represent over 90% of the total emissions of F-11, -12, -113, and -114 in the overall area of refrigeration and air conditioning.

Home Refrigerators and Freezers

Current home refrigeration systems (refrigerators, freezers, ice makers, and dehumidifiers) are well-engineered hermetic units for which extensive practical efforts have been made by the manufacturer to minimize chlorofluorocarbon emissions (R-12) over the life of the product.

Current best manufacturing practice includes the use of silver brazed joints, special transition joints for attaching aluminum and copper tubing, proper design to eliminate vibration from the motor-compressor unit, direct connection of components over the shortest practical distances, and relatively thick wall tubing. Manufacturers pressure test components prior to assembly and insist on thorough in-house quality control programs utilizing highly trained production personnel.

Losses from the current systems appear to be minimal for normal operation (i.e., excluding accidental damage) during their lifetimes. Additional engineering developments are not likely to produce a major reduction of the emissions from this source, and the benefit would not appear to be commensurate with the probable costs.

Service repair practices in the field vary widely depending on the individual, repair tools and apparatus available, prior training and experience, equipment to be serviced, etc. One common practice found in the field is to vent to the atmosphere any remaining refrigerant in the home unit. There is no attempt to salvage the refrigerant because of (1) fear of possible refrigerant contamination and subsequent damage to the unit, and (2) unfavorable economics for which servicing costs outweigh the dollar value of the refrigerant.

No new operating and/or maintenance practices within the refrigeration industry to reduce refrigerant emissions were found. The practice of atmospheric venting of small amounts of refrigerant in home units will probably continue in the near future.

No new developments in reclamation and/or recycling of refrigerants is foreseen in the near future. Present large-scale technology is adequate but under-utilized.

Mobile Air Conditioning

Previous studies on chlorofluorocarbon use and emissions indicate that mobile air conditioning is both the largest user and emission source among the refrigeration end-use applications. Annual emissions are divided between major leaks, minor leaks, service-related purging, and disposal of old systems. Minor leak sources, which frequently occur and account for the majority of current emissions, include: the compressor shaft seal, hose permeation, compressor gaskets and fittings. The major leak sources, which seldom occur but contribute significant emissions because the entire refrigerant charge is lost, include auto accidents, hose bursts, fatigue of metal lines and compressor failures. Service related emissions include venting any charge which remains in the system to the atmosphere by service shops and "do-it-yourself" addition of refrigerant which can contribute to emissions by postponing needed repairs. Salvage yards indicate that only 25 to 50% of air-conditioned automobiles received have any charge remaining in their systems.

Improvements in hardware component design and use which might reduce emissions include tighter specifications for and quality of compressor shaft seals, increased development and use of hoses with low permeation liners or substitution of flexible metal hoses, improved gasket materials, and better inspection of line fittings during assembly and use. Improvements in the basic system design include the addition of component isolation valves, reducing the number of and improving the design of gasket and compressor joints, and using brazed joints to connect components whenever possible. A major design change would be the development of a hermetic system.

Possible changes in operating, service, and disposal procedures include periodic operation of the compressor during long periods of nonuse, elimination of do-it-yourself recharging kits, better leak detection by service shops, elimination of unnecessary purging, and institution of refrigerant recovery procedures when servicing or scrapping systems. Recovery and recycling of refrigerant from mobile air conditioners is technically feasible but rarely practiced because of economics.

Chiller Systems

The total number of chiller units in operation is relatively small compared to the overall number of air-conditioning units. The importance of this area, however, lies not in the number of units, but in the relatively large refrigerant charge of each unit. This large charge has the potential for emission of considerable quantities of refrigerant to the atmosphere in a single incident.

In terms of mechanical equipment, pressure relief valves offer the greatest potential for the total loss of the refrigerant charge in a single incident. These devices are required by building codes as safety measures. Two types of pressure relief valves are commonly used: a rupture disc device and a mechanical spring-valve arrangement. Both of these devices can occasionally release refrigerant at pressures below the rated pressure and, in addition, can be sources of continual low-level leakages. The solution to the problem appears to be in better quality control rather than in the development of a new relief valve. Purge systems (low-pressure units only) are a continual source of refrigerant emissions. Reduced air leakage into the low pressure units would result in less frequent purging. More efficient purge systems can be developed which would decrease refrigerant emissions by at least 67% at an estimated cost for the new purge of about three times that of the present one. However, the current cost of the purge system is relatively small compared to the overall cost of the system. Sources of continual, low-level leakage are gaskets, valves, compressor seals, and flanged joints. In general, detection of leakages at these sources and prompt replacement of the defective part would reduce emissions to a considerable extent. In certain instances, new types of equipment could be installed for basically the same cost as present equipment.

Service and repair operations are a source of considerable deliberate emissions of refrigerant to the atmosphere. Recovery and recycling systems are available but, as with the other areas of refrigeration and air conditioning, economic considerations are important.

Commercial Food and Beverage Systems

The majority of the present state-of-the-art commercial refrigeration systems (utilizing R-22 and R-502) employ a single condensing unit connected in parallel to one or more refrigerators having identical utilization. The total refrigeration systems for large supermarket operations are well-designed to minimize refrigerant losses, but, because of the overall complexity of the system, many potential emission points exist. These include failure or pinhole leaks at welded or brazed joints (including transition joints, fittings, and elbows), isolation valves, head gasket plates on the semihermetic motor-compressor units, and condenser and evaporator failure, etc.

Old refrigeration systems (utilizing R-12) for large supermarkets are usually "compounded" operations in which one large compressor and one small compressor are arranged in parallel and serve several display cases, coolers, and freezers through a complicated system of valves, piping, and a common condenser. Because of inherent design complexities in these systems, the previous comments regarding potential refrigerant emissions sources are equally valid.

Older refrigeration systems for small stores often rely on a number of individual belted, open-compressors serving three or four display cases, coolers, or freezers. Sources of refrigerant emissions include the compressor crankshaft seals, the cylinder head gasket, various isolation and purge valves, and vibration sensitive joints and seals, etc. These older commercial systems often have an unneccesarily large number of joints, fittings, and valves as the result of growth by addition of more display cases.

The trend in commercial food and beverage refrigeration is to convert older operations to modern systems using separate R-22 and R-502 systems. Alternatively, older small stores may remodel and employ a series of R-12 hermetic, self-contained refrigeration cases. Either choice leads to a reduction in refrigerant emissions. Conversion costs are substantial, however, and are generally passed on to the consumer.

No comprehensive new engineering developments to reduce refrigerant emissions in commercial food and beverage refrigeration systems are foreseen in the near future. Improvements will continue to unfold slowly on a broad front as component manufacturers improve their product lines.

Service repair practices in the field vary with the age, size, and complexity of the commercial refrigeration systems. Generally speaking, the problem area will be located and isolated, thereby defining a limited quantity of refrigerant to be purged to the atmosphere or possibly salvaged for recycling. Methods for the recovery of small quantities of used refrigerant are currently available. Large scale systems for the recycling and storage of used refrigerant are available at a cost of $15,000 to $20,000.

FOAM BLOWING AGENTS

The 1975 consumption of chlorofluorocarbons as blowing agents in plastic foams is estimated at 80 to 84 million pounds, roughly 9% of the total U.S. production. Flexible and rigid urethane foams account for more than 90% of total usage of chlorofluorocarbons as blowing agents. While rigid foams consume over 70%, direct atmospheric emissions from flexible foams are three to four times greater than direct losses from rigid urethane foams. The reason for this diparity is that blowing agents are largely retained within rigid foams, while virtually all chlorofluorocarbons used in flexible foams promptly diffuse into the atmosphere.

There are presently no emission controls employed to collect and treat chlorofluorocarbon vapors evolved in producing plastic foams. A survey of (1) major foam producers, (2) suppliers of foam ingredients, (3) foam production equipment manufacturers, and (4) solvent vapor recovery or emission control purveyors indicates that, not only is there no chlorofluorocarbon control technology in present use, but there has been little or no consideration given to the possible need for any type of control.

Much of the basic information that would be required for the design and development of chlorofluorocarbon vapor recovery systems has not yet been collected. Among the most critical data needed are:

* How much blowing agent is lost from foams at various stages or steps in production?

* What are the rates of chlorofluorocarbon diffusion out of foams over the period of generation and subsequent processing?

* Where are the best locations for the collection of blowing agent vapors with least complication of commercial production?

* What are the current levels of chlorofluorocarbon vapor concentrations at various points along the processing sequence; and the existing concentrations in the present ventilation and exhaust air systems?

* And perhaps of greatest importance--Can significant fractions of the chlorofluorocarbon vapors be collected using sufficiently low rates of air flow to make vapor recovery less costly?

Only one or two persons among the experts surveyed could even venture estimates regarding these unknown factors. Among foam producers, only one company reported recent (July 1976) attempts to measure chlorofluorocarbon levels throughout the foam line and exhaust air. Clearly it will be necessary to obtain actual analytical data of the type indicated. This needs to be done before detailed evaluations can be made of either the technical feasibility of chlorofluorocarbon recovery, or the effectiveness of any proposed control system in reducing emissions to the atmosphere. All of these engineering aspects should be clarified before additional economic assessments can be performed.

This study, therefore, has attempted to ascertain the extent to which it may be feasible to control chlorofluorocarbon emissions in foam production. For the urethane foams, each of the major production processes was examined. Those features of each process that affect the consumption and losses of blowing agent were identified and discussed. For six major types of foam processes, a representative "model plant" has been defined in terms of mass balance, processing steps and estimated losses of blowing agents. For each of the six major processes, the approximate distribution of chlorofluorocarbon losses at various stages of production has been compared.

Of the existing solvent vapor control processes, only activated bed adsorption appears technically suitable for recovering chlorofluorocarbon vapors, at relatively low concentrations, from fairly high volume air streams. There are a few problems specifically related to the chemical and physical properties of the vapors to be treated; but none that pose serious obstacles to the use of this established technology. Carbon adsorption systems regularly exhibit recoveries of 93 to 98% of the solvent vapors passed through the sorbent beds.

If sorption systems were applied for recovery of chlorofluorocarbons from various stages of plastic foam production, it should be possible to reduce total foam plant emissions by 49% up to 75% of present losses. For flexible urethane foams, the recovered chlorofluorocarbons represent a corresponding reduction in total blowing agent purchases. In the case of rigid foams, only 9 to 15% of total chlorofluorocarbon consumption could be recovered.

Preliminary economic analysis shows that savings due to chlorofluorocarbon recovery may exceed total annualized costs for recovering fairly large quantities of blowing agent vapors. Similarly, favorable ratios of savings to cost are attainable for recovering moderate amounts of chlorofluorocarbon vapors using automatic packaged sorption units.

CLEANING AND DRYING SOLVENTS

These applications represent areas in which the chlorofluorocarbons play a relatively minor role both with respect to the total quantity of solvents used and to the overall consumption of chlorofluorocarbons among the use areas. The consumption of F-113 and F-11 in this application represents only approximately 6% of the total solvents used for cleaning and only about 9% of the total consumption of the five chlorofluorocarbons.

The use of F-113 and F-11 in the cleaning and drying field is concentrated in the electrical and electronics industries for the defluxing of printed circuit boards (PCB's) and the cleaning of electronic parts, electric motors, and delicate electronic and scientific instruments. As a dry-cleaning agent, F-113 is used primarily in coin-operated type machines run by trained personnel. The general public has little contact with F-113 as a dry-cleaning solvent.

For cleaning and drying applications, other than dry-cleaning, the major sources of solvent emission are evaporation, dragout, and used solvent disposal. The specific quantity of solvent loss attributable to each source is dependent upon the configuration of the part being cleaned or dried. The methods of emission control considered were carbon adsorption systems, increased freeboard height, freeboard chillers, refrigerated freeboard chillers, covers, and offset-sump systems. Distillation equipment was considered for the recycling of used solvent. Operating practices were found to be an important factor in the quantity of solvent lost by evaporation and dragout.

The efficiency of each method of emission control has been estimated. These efficiencies range from approximately 35 to 65% dependent upon the specific method. All of the identified emission control methods, except carbon adsorption and used solvent distillation, are directed towards a reduction in the quantity of solvent lost from the machine. Almost all of the methods are shown to be economically feasible because the calculated savings/cost ratios are greater than 1.0, which is the break-even point. The use of covers and an increased freeboard height show the largest economic advantage.

Carbon adsorption systems are designed to collect and recover solvent vapor from the atmosphere immediately above the machine. Adsorption efficiencies of the carbon bed are approximately 95% for F-113 so that the overall system efficiency depends upon the solvent vapor capture efficiency. Azeotropic mixtures containing water-soluble components cannot be recovered by this method. Distillation of used solvent can be easily accomplished and was found to be economically feasible. Solvent recovery by distillation of the order of 85 to 90% can be obtained. More careful adherence to good operating procedures can also be effective in reducing solvent loss, but because this area concerns human nature, it is difficult to assign any specific efficiency for reduction of emissions.

The dry-cleaning industry represents an area where a very costly solvent (F-113) competes with two low-cost solvents. Systems utilizing F-113 are, of necessity, carfully designed to minimize solvent loss in order for the use of F-113 to remain competitive.

SECTION III

REFRIGERATION AND AIR CONDITIONING

This section of the report addresses the sources of refrigerant emissions and the technical and economic aspects of emission control methods, including service operations and refrigerant recovery techniques. The discussion is specifically concerned with those systems employing R-11, R-12, R-113, and R-114 in the following classifications of the refrigeration and air conditioning sector:

1. Home refrigerators and freezers,
2. Mobile air conditioning,
3. Industrial centrifugal and reciprocating chillers, and
4. Commercial food and beverage refrigeration.

Other areas of refrigerant usage, such as home (room and central) and small commercial air conditioning systems, commonly employ other refrigerants and thus are excluded from consideration in this study.

According to a published report, the entire area of refrigeration and air conditioning accounts for 26% of the total chlorofluorocarbon emissions from end-use applications. Within the total area of refrigeration and air conditioning, mobile air conditioning accounts for 33.3% of the total emissions. Industrial centrifugal and reciprocating chillers account for 22.8% and food store and beverage refrigeration contributes 14.5%. Both of these figures include contributions from R-22 emissions. Home refrigerators and freezers contribute 2.2% of the total refrigeration and air conditioning emissions. Other types of equipment either employ refrigerants outside the scope of this study or contribute less than 1% of the total emissions in this end-use area.1/

Because the units considered in this section are mechanical systems presenting several probable sources of refrigerant emissions which vary in leakage intensity from unit to unit, it is not possible to quantify the amount of emissions from specific point sources in any terms other than major or minor. To our knowledge, few, if any, studies have been conducted which attempt to quantify an average leakage from specific point sources. Many specifications are stated but the actual performance of a specific part or material under operating conditions is not well established.

In the following subsections concerning each of the four refrigeration and air conditioning systems, the sources of refrigerant emissions and the technical and economic aspects of emission control techniques will be discussed for each system.

HOME REFRIGERATORS AND FREEZERS

The total home refrigeration market is nearly 10 million units including imports (approximately 0.8 to 0.9 million). Market saturation is virtually complete for refrigerators (~ 100%) with replacement sales nearly 80% of total sales. The home freezer market is far from saturation (~ 45%) but growing as consumers continue to take advantage of seasonal prices and purchase foodstuffs for future use. Replacement sales are likewise growing and amount to an estimated 38% of total freezer sales.2-6/

The refrigerator consumer market is dominated by GE/Hotpoint, Whirlpool, and White (Westinghouse) which jointly account for 68% of all retail sales. The freezer consumer market is dominated by White (Westinghouse) and Whirlpool and account for 53% of total retail sales. A published summary lists all manufacturers and their market shares.5/

The home refrigeration industry consists of approximately 10 large manufacturing companies and perhaps a thousand component manufacturers, wholesalers, and distributors. The test equipment and service and repair industry of some 300,000 individuals serves this economic sector. The total economic value of the entire refrigeration industry including peripheral suppliers and the service industry probably is $10 billion annually.6,7/ This is close to 0.6% of the Gross National Product.

Estimated Refrigerant in Use and Annual Losses

The total amount of R-12 refrigerant in the home refrigerator and freezer sector is probably in the range of 85 ± 10 million pounds. This calculation is based on an estimated 73 million homes having at least one refrigerator and an estimated 32 million homes having at least one freezer, and the additional assumption of 0.63 and 1.25 lb of refrigerant per unit for refrigerators and freezers, respectively.3/

The current replacement sales rate of approximately 81% of annual refrigerator sales and a corresponding 38% replacement rate for freezers permits an estimate of 4.6 million refrigerators and 1.14 million freezers which could be discarded in 1976. However, it is not uncommon for the "old" refrigerator to be placed in a basement or garage for additional storage purposes. Using the above figures, approximately 4.3 million pounds of refrigerant are potentially available for release to the environment either through gradual leakage or catastrophic rupture as in scrapping of the unit.

Refrigerator and freezer average lifetimes have been extended as the product line improves. Current estimated average lifetimes before replacement for standard-sized refrigerators is about 15 years, whereas the compact refrigerators have an average lifetime of approximately 10 years. For freezers, the average lifetimes are 18 years for the standard size and 12 years for the compact size.[3]

Refrigerators are discarded for many reasons, some of which are not related to refrigerant loss, and a high percentage of discarded units may arrive at a disposal center (dump) with a full charge of refrigerant which can be suddenly released if the unit is crushed for scrap or buried in a landfill. In essence, the total potential of 4.3 million pounds of refrigerant annually discarded probably does enter the atmosphere each year. No attempt is made to salvage and recycle even the recoverable portion of this quantity since the average home refrigeration unit contains much less than $1.00 worth of refrigerant.

Other home refrigeration units using chlorofluorocarbons falling within the scope of this report include dehumidifiers and ice makers. The combined market for these units is approximately 10 to 15% of the refrigerator market.[6,8] The total refrigerant charge of scrapped dehumidifiers and water coolers in 1976 is estimated to be 0.2 ± 0.1 million pounds.[6] Hence, the total annual available refrigerant charge for release into the atmosphere during discard or scrapping operations of major home appliances is approximately 4.5 million pounds, principally as R-12.

Table III-1 presents a summary of estimated major home appliance refrigerant usage as original and replacement charge for 1976.

Table III-1. HOME REFRIGERATION USAGE AND REPLACEMENT IN 1976

Major appliance	Units shipped in 1976 (million)	Original charge million (lb)	Unit replacement sales (million)	Average unit charge (lb/unit)	Total replacement charge (million lb)
Refrigerator	5.7	3.6	4.6	0.63	2.9
Freezers	3.0	3.8	1.14	1.25	1.4
Dehumidifiers	0.48	0.4	0.16	0.48	0.13
Ice makers	0.15	0.3	0.03	2.00	0.06
Total		8.1			4.5

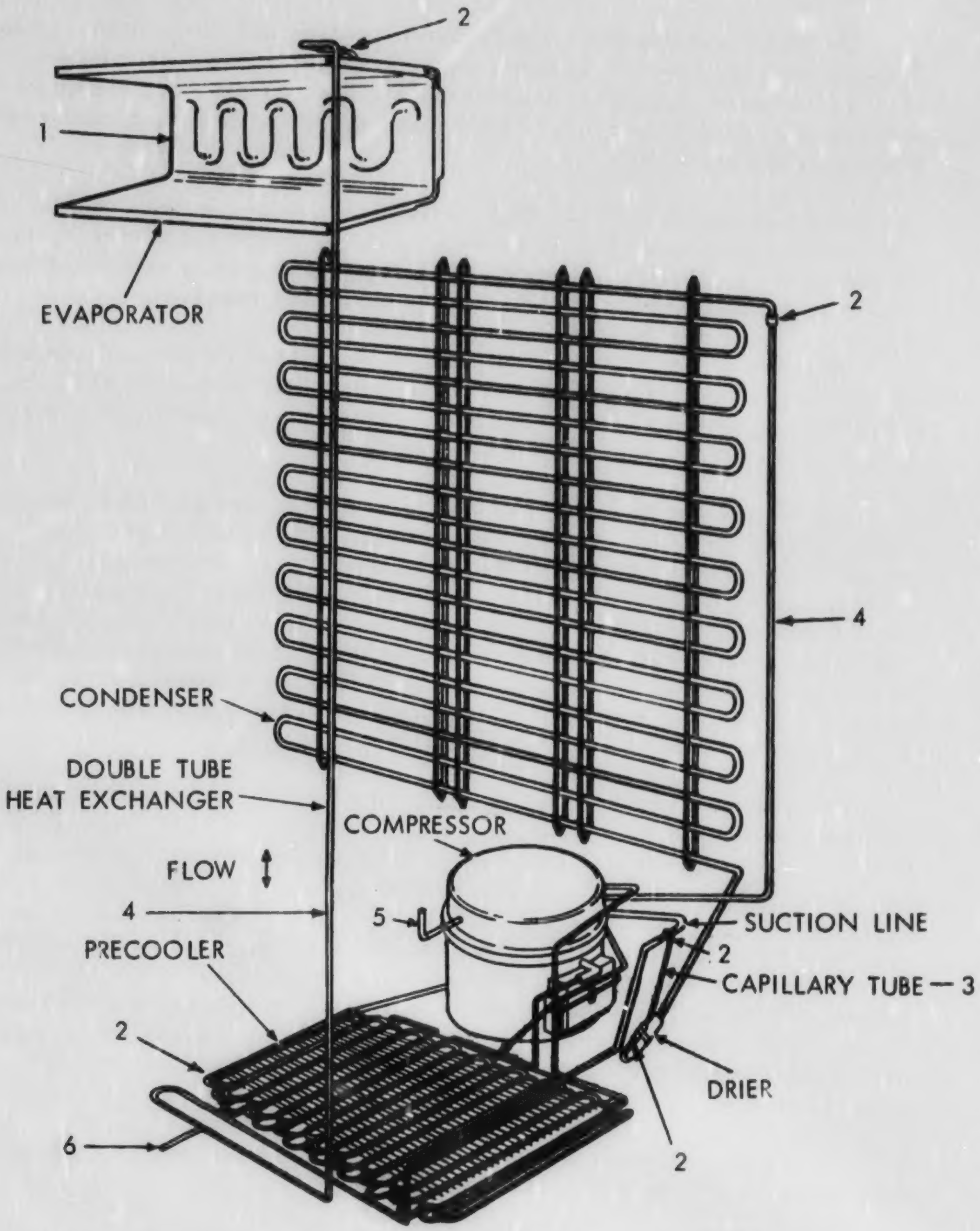
Source: References 4 through 6 and 8.

From a macroeconomic viewpoint, due to the relatively long history of consumer refrigeration in the United States, an approximate "steady state" condition has been achieved between production and consumption (or discard) of refrigeration units. Although in any given year, e.g., in 1976 some 8.1 million pounds of chlorofluorocarbons will be used in producing new consumer refrigeration units, some 4.5 million pounds or ≃ 56% of the refrigerant will be "discarded" or have the potential for release into the environment via leakage, catastrophic failure, scrapping and/or landfill operations.

Sources of Refrigerant Emissions

The present hermetically sealed home refrigerator or freezer consists of a single unit in which the motor, compressor, condensing and evaporating coils, and various other components are assembled in such a manner as to provide a leak-proof system with a minimum number of joints. The adjective "leak-proof" is relative and depends on the degree of sophistication of the test method, e.g., pressure- and/or bubble-immersion tests, E. I. du Pont de Nemours Dytel® organic dye technique, the halide torch, electronic halogen leak checker, and mass spectrometric techniques including the use of helium gas, etc. Generally speaking, the less sophisticated techniques are more prevalent. The pressure/bubble tests are used more often than the more sensitive electronic halogen leak detector or the highly refined mass spectrometric techniques.

Figure III-1 presents a schematic diagram of current hermetic home refrigeration or freezer systems. The various arrows indicate potential refrigerant emission points.


2
1
EVAPORATOR
2
4
CONDENSER
DOUBLE TUBE
HEAT EXCHANGER
COMPRESSOR
FLOW
4
5
SUCTION LINE
2
CAPILLARY TUBE — 3
PRECOOLER
2
DRIER
6
2

Source: Adapted from Whirlpool Corporation refrigeration products service manual.

Figure III-1. Typical hermetically sealed home refrigeration unit

The major refrigerator manufacturers, Whirlpool Corporation, Amana Corporation, GE/Hotpoint Company, etc., internally manufacture some or all of the motor-compressor housing units, heat exchangers, condenser and evaporation coils, fans, cabinets and doors, plastic and rubber components, and insulation.

These companies heavily rely on subcontractors for some or all of their motor-compressor units, valves, tubing, electrical controls, transition joints, gaskets and seals, insulation components, rupture discs, refrigerant, and service and repair equipment and supplies.

Some condensing units are placed in the bottom of the refrigerator or freezer cabinet along with the motor/compressor hermetic unit. The condenser is either a simple convection type (static condenser) or a forced convection type (blower condenser).

The evaporator is generally made of aluminum and provides the basic volume for frozen food storage, ice making, and general cooling of the entire refrigerator or freezer cabinet. Connections between the evaporator, condenser, and the motor-compressor are either aluminum or copper tubing which is silver brazed or helium-arc welded. Various other components, i.e., the starting relay switch, protective fuses, temperature sensing devices, defrosting heater coils, door switch, etc., complete the system. The complete refrigerant circulating system is designed to be removed in one piece for servicing convenience.

Refrigerator and freezer manufacturers generally pressure test (with and without immersion) system components prior to assembly through inhouse quality control programs. After brazing and assembly, the entire system is pressure tested. If the system appears satisfactory, it is filled with the proper refrigerant charge and leak-checked during an initial break-in period. Only satisfactory systems are finally installed in refrigerator and freezer cabinets. Unsatisfactory systems are reworked and re-checked with a leak detector for satisfactory performance. By use of an intensive quality control program, relatively few defects are found after refrigerant is placed in the system. Industry-wide re-work rate is of the order of 0.5%.[9,10/]

The common emission sources, denoted by numbered arrows in Figure III-1, correspond to the following:

1. Rupture of evaporator due to accidental puncture, corrosion or flaw in the component.

2. Failure at a brazed joint (various potential locations) due to corrosion, faulty brazing technique, excessive vibration, physical abuse, flaws, etc. Particularly troublesome are the copper/aluminum transition joints between the aluminum evaporator and copper lines.

3. Accidentally broken capillary tube.

4. Failure of a connecting line due to a flaw or high pressure in the flow system.

5. Leakage from a manufacturer's process tube (pig-tail).

6. Leakage from the point on a line where a service (saddle) valve had been installed by service repairmen in the field.

In hermetically sealed units, all joints are silver brazed and/or helium-arc welded. Service valves may or may not be present depending upon the manufacturer.

Current refrigeration manufacturing technology, e.g., at the Whirlpool and Amana Corporations, specifies the use of silver brazed joints or helium-arc welded aluminum tubing, direct connection of the various components over the shortest practical distances using relatively thick wall tubing, and no service valves. The compressor and motor are sealed in a common housing thus eliminating the compressor crankshaft seal which has been a particularly troublesome emission point.

Older refrigeration assembly techniques included various flanged joints or mechanical compression seals, conventional soft solder, and flanged service valves. The Schrader valve, which is basically an automotive tire valve fitted with special chlorofluorocarbon resistant gaskets, seals or O-rings, and a gasketed valve cap, is still used on some refrigeration equipment but not on the standard hermetically sealed refrigeration units. These valves are common sources of leakage. Soft solder joints tend to fail due to vibration and/or corrosion and have long been discontinued.

The causes of low refrigerant level in hermetically sealed units include all of the above categories; the most frequent categories are the aluminum/copper transition joint, any joints associated with the high pressure side of the motor-compressor unit, and corrosion of the aluminum evaporator. Physical damage to the unit by sharp objects such as ice picks being improperly used still occur. No statistical data base exists at present to rank the various categories.

Service and Repair Operations - It is not known exactly how many air conditioning and refrigeration service repairmen there are in the United States today. The U.S. Department of Labor indicates there were about 135,000 air conditioning, refrigeration, and heating installation and repairmen employed in 1972, most of which were employed by cooling and heating dealers and contractors.[11] It is felt that these data are low and data from other sources have been used.[47]

There were approximately 3,000 service repair establishments with payrolls amounting to $305 million annually in 1972 and employing 10,274 persons.[12] The largest concentration of service shops appear in New York State, California, and Texas. Regionally, the South accounts for 41% of the service shops. An independent industry source estimates there are perhaps 50,000 to 75,000 self-employed service repairmen (independent jobbers).[3]

Table III-2 estimates the number of service repairmen in various employee categories. This information was compiled from various sources and is the best estimate obtainable of the total work force capable of installing and servicing refrigeration and air conditioning systems.

Table III-2. AIR CONDITIONING AND REFRIGERATION SERVICE REPAIRMEN IN THE U.S. IN 1976 BY CATEGORY

Worker category	Estimated No. of service repairmen	Reference source
Self-employed	50,000-75,000	13
Service repair establishment employees (2,868 fix-it shops with payrolls)	10,274	12
Manufacturers, wholesalers, distributors, and retail store employees (local, regional, and national)	7,500-15,000	6
Commercial and industrial service organization employees	2,000-3,000	6, 14
Contractor and builder employees	200,000-250,000	6, 47
Total service repairmen	270,000-353,000	

Regarding service repair practices for home refrigeration, much depends on individual training and preference in handling various kinds of refrigerant leakage problems. Factory-trained servicemen (e.g., Carrier Corporation, Whirlpool Corporation, etc.) are supplied with service manuals and procedures for specific brands and models of equipment. Independent service repairmen may not possess this kind of information and will proceed to repair a leak based on individual experience with varying kinds of equipment.

In general, service repairmen are hesitant to salvage refrigerant for direct recycling unless they are certain it is not contaminated with water, oil, greases, dirt and dust, finely-dispersed solids, nor partly decomposed due to compressor burn-out. The service repairman does have the option of collecting any remaining refrigerant for reprocessing by distillation.

In the opinion of several industry spokesmen, few attempts are ever made by service repairmen to recover refrigerants from small systems such as would be found in the home. The reason for the present practice of venting small quantities of refrigerant to the atmosphere is economics. Each home refrigeration unit (refrigerator, freezer, dehumidifier or ice maker) contains 0.6 to 2.0 lb of refrigerant per unit and has an intrinsic value of only $0.40 to $1.20. The cost of placing a service repairman in the field together with test equipment, tools, repair kits and apparatus, etc., is approximately $25.00/hr in 1976.[17] If 30 min time is required for transfer, labor charges are $12.50.

Methodologies to Reduce Losses

Hardware Improvement - Several manufacturers of home refrigeration units, as well as component manufacturers and service repair shops, were contacted to inquire of methodologies, e.g., hardware improvement, new operating or maintenance practices and procedures, etc., to reduce and/or eliminate refrigerant losses in the field. Invariably, these sources considered the present hermetically sealed system to be "near perfect." The rationale of this position is that the home refrigeration system has evolved over the past 50 years with engineering emphasis being placed on the development of the motor-compressor single-housed unit, the development of superior motor insulation and gasketing materials, increased use of brazed joints, improved engineering design, newer refrigerants, etc.

The present manufacturing philosophy is to avoid complicated system designs and any extra or unnecessary connections or service valves. No new major developments are immediately foreseen by manufacturers with regard to refrigerant losses in the field.

Recent improvements in hardware design to reduce refrigerant losses include proper engineering design of the total refrigeration system to eliminate or reduce known potential trouble spots, including shorter connectors, fewer fittings, heavier wall aluminum and copper tubing, etc.

In addition, product improvement has been accomplished through manufacturing quality control testing programs, better trained manufacturing personnel, and improved leak detection techniques at the point of manufacture, including leak testing prior to and after final assembly.

Whirlpool Corporation has conducted an engineering cost feasibility study to replace chlorofluorocarbon-blown insulating material with a vacuum-Perlite combination insulation for refrigerators and freezers.9/ Through actual construction of vacuum-Perlite test panels and installation, sufficient technical information was attained for a critical assessment of the project. An insulating value of 5/8 in. thick vacuum-Perlite combination was equivalent to a 3 in. thickness of Fiberglas®. However, technical difficulties were encountered in the filling process. The project is inactive at the present time.

No engineering development cost feasibility studies to reduce refrigerant emissions from hermetic systems have been found. This is not to be interpreted as meaning that such engineering development cost studies do not actually exist, but rather that manufacturing companies or component manufacturers guard these developments closely. Although leakages from hermetic systems are considered small problems, new developments could provide a competitive advantage. One industry spokesman suggested that if such studies had been completed by a refrigeration company which pointed to positive conclusions regarding design and/or operating practice changes for a product line, such a company would not prematurely reveal this event for it could lead to loss of a potential competitive advantage.18/

Thus, the home refrigeration industry is in an apparent "stand-pat" stance although it is quite possible some positive changes in product performance and improvement in refrigerant losses may be forthcoming in the near future.

Present industry hardware research and development efforts are in the direction of reduction of energy consumption for the same cooling capacity. A recent Compressor Technology Conference at Purdue University brought forth a series of compressor efficiency and performance papers related to energy consumption.19-21/

Whirlpool Corporation and Amana Corporation are both considering installation of alarms or electronic consoles with self-diagnosing circuits and indicators to warn the consumer of low refrigerant level, excessive heating and pressure surges, etc. Such alarm systems will be doubly costly to the consumer since the research and development costs will tend to be passed on to the buyer and the alarm systems consume additional electrical energy; however, these costs will be partially balanced by early detection of equipment malfunction.

Operating and/or Maintenance Practices - No new operating and/or maintenance practices or procedures within the refrigeration industry to reduce refrigerant emissions were found. Industry spokesmen prefer to emphasize adherence to manufacturer's manuals for recommendations regarding operation and maintenance of home refrigeration units.

A standard reference book for refrigeration and air conditioning directs the repairmen to purge the system of refrigerant prior to servicing.[22/] A service manual from a large refrigeration manufacturer also directs purging of the refrigerant to the atmosphere with no recommendation for recovery. In contrast, a recent article in Air Conditioning and Heating News describes simple equipment and techniques for recycling refrigerant from domestic refrigeration units after servicing the equipment.[16/] However, in the opinion of the authors of this report, the article merely constitutes "wishful thinking" in discussing recovery and recycling techniques of home refrigerants. Such practices in the field would not be attempted due to poor economics as previously described.

Small leaks in hermetically sealed systems are frequently ignored as being uneconomical to repair. It may be difficult to educate owners of home refrigeration systems to check for small leakages. A built-in detection system such as the E. I. du Pont Dytel® organic dye technique may be quite useful. However, some type of incentive would be required to encourage owners to periodically check their units for leakages.

Vibration may be a cause or contribute to a fatigue failure and a catastrophic failure resulting in a loss of the refrigerant charge. The service repairman should check for excessive vibration and insure that the unit is level.

Recovery and Recycling Systems for Refrigerants - If the recovery and recycling of refrigerant from home refrigerators were to become mandatory by law, in spite of the unfavorable economics, there must be rapid and convenient techniques and apparatus available. Refrigerant R-12 can be transferred by pressurizing the system and capturing the refrigerant in a cooled refrigerant cylinder. Several companies supply refrigerant handling and measuring equipment.[23/] One type of recovery system is available for approximately $700.[15/]

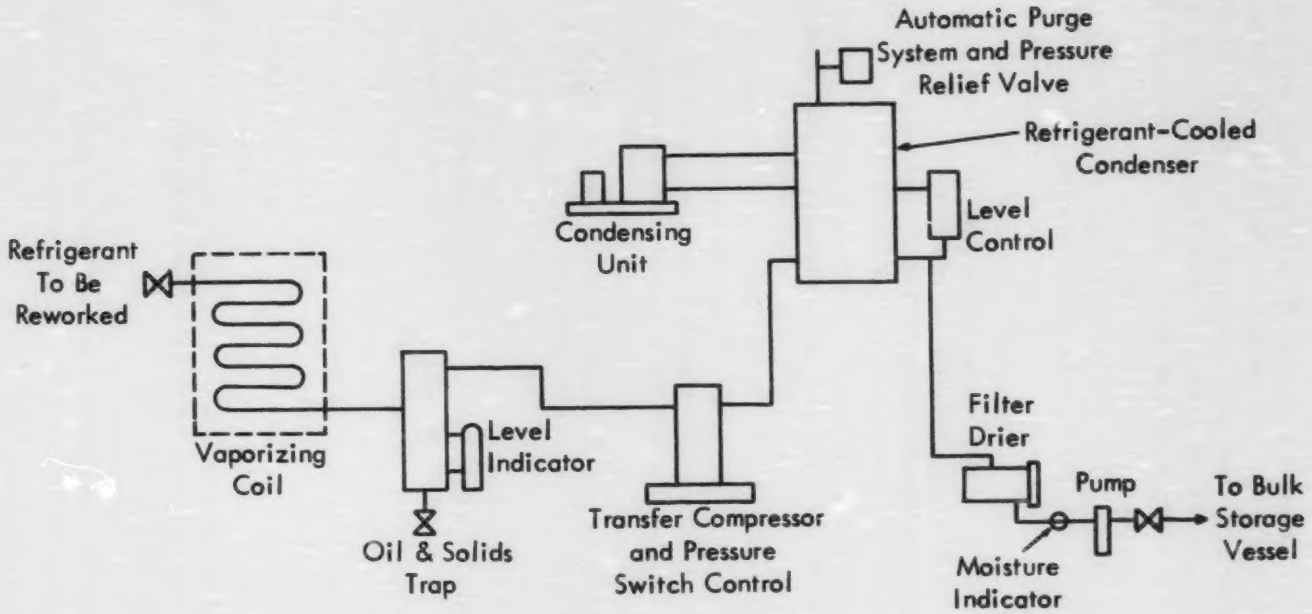
Another possible recovery method would involve the use of a stainless steel gas cylinder (e.g., DOT "G" cylinder) equipped with a pressure gauge and a transfer pump, which most service companies have available. A "G" cylinder can be purchased for less than $200. If it is assumed that an average refrigerator in need of service contains 0.5 lb of R-12, up to 30 refrigerators could be emptied using the same recovery cylinder. It is doubtful that a serviceman would repair more than five to six refrigerators in a single day. For safety reasons, this method should be used only by personnel thoroughly familiar with gas transfer procedures. The gas in the cylinders should be emptied at the end of each day.

The E. I. du Pont Company has developed a refrigerant reclamation systems for either R-12 or R-22 for use by original refrigeration unit manufacturers.[24] The equipment removes oil, solid contaminants, moisture, and noncondensibles from the contaminated refrigerant by pumping the fluid through a series of vaporization steps, traps, condensers, and driers. The basic unit cost is approximately $10,000. It is claimed the savings resulting from the equipment installation will earn back the investment in a reasonable (unspecified) period. Figure III-2 illustrates the basic features of the refrigerant reclaimer. The standard design does not include a storage vessel. An air operated diaphragm pump transfers the clean dry refrigerant back to the manufacturer's plant refrigerant storage tank. Piping from rework areas to the reclaimer and from the reclaimer to storage is the customer's responsibility. The total cost to the customer is approximately $15,000 to $20,000 for the basic unit, storage vessel, piping, additional pumps, and other accessories.[6] Only one basic reclamation unit has been sold by Du Pont Company to date.

The E. I. du Pont Company has also developed an F-11 solvent cleaning system for large scale refrigeration systems with burned-out compressor units. The procedure directs the user to discharge the contaminated refrigerant to the open atmosphere. Fresh F-11 is circulated through portions of the system by a diaphragm pump which develops a strong pulsating action to mechanically scrub and scour interior system surfaces. The F-11 used for cleaning can be recycled, especially if a strainer and filter-drier have been used in the solvent return line. The cleaning system costs between $850 to $900[25] and is available from an independent company, F. F. Slocomb Corporation.

MOBILE AIR CONDITIONING

An estimated 45 million mobile air conditioning units were in service in 1973. These were primarily factory-installed auto air conditioners, but also included air conditioning installation in light trucks,


Automatic Purge System and Pressure Relief Valve
Refrigerant-Cooled Condenser
Level Control
Condensing Unit
Refrigerant To Be Reworked
Vaporizing Coil
Level Indicator
Oil & Solids Trap
Transfer Compressor and Pressure Switch Control
Filter Drier
Pump
To Bulk Storage Vessel
Moisture Indicator

Source: Adapted from E. I. du Pont Refrigerant Product Information Bulletin RT-58.

Figure III-2. Refrigerant reclamation system

RV's,* busses, and add-on air conditioners. It was also estimated that 7.53 million new mobile air conditioner units were installed and 7.00 million units were scrapped in 1973. All of these units used R-12 except for those in busses and some RV's which may use R-22.[1] Estimates for succeeding years are not complete. Data for factory-installed auto air conditioners indicate that although the installation rate declined from 7.3 million units in 1973 to 5.6 million units in 1974, and to 4.9 million units in 1975, the percentage of new cars equipped with air conditioning has remained nearly constant, with 73.8% of 1973 models, 68.2% of 1974 models, and 72.2% of 1975 models being factory equipped.[26] In effect, neither the trend toward smaller cars, a heightened desire to conserve energy nor concern for chlorofluorocarbon emissions have dampened the popularity of one of the auto industry's most expensive options. If the production decline of new cars because of the economic recession was accompanied by a similar decline in the scrappage rate, approximately 47 million mobile air conditioners are in use at this time. By comparison, an estimated 105 million total automobiles and 25 million other vehicles are presently in use.[27] Therefore, about 40% of all registered motor vehicles in the United States are air conditioned.

Mobile air conditioning contributes to the large economic impact of the automotive industry. In 1974, the automotive and related manufacturing was estimated to be an $85 billion per year industry.[27] The dollar amount which is directly attributable to auto air conditioning is not exactly known. Factory installed air conditioning, which usually adds $400 to $500 to the selling price of new cars, would account for about $2.5 billion for new car sales of about $28 billion.

Mobile air conditioning also has a large employment impact. In 1972, there were 3,826 establishments with 1.3 million employees engaged in automotive-related manufacturing, 67,654 establishments with 0.5 million employees engaged in wholesale automotive-related sales, 328,206 establishments with 1.9 million employees engaged in automotive-related retailing, and 168,959 establishments with 0.5 million employees engaged in automotive-related servicing.[27] No information could be found which specifically identified the proportion of establishments or employees directly engaged in mobile air conditioning activities. It has been estimated that approximately 50% of the 200,000+ service stations in the United States also engage in mobile air conditioning service activities of various types.[39]

The most recent comprehensive estimates on chlorofluorocarbon use and emissions available for mobile air conditioning were made for 1973.[1]

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* Recreational vehicles.

From the A. D. Little report, it is calculated that the refrigerant present in the 45 million units would total 171 million pounds if all were fully charged.

Charging of new units produced during 1973 required 28.6 million pounds of refrigerant, and, from calculations based on the A. D. Little data, replacement of that lost through leakage or service required 44.3 million pounds for mobile air conditioning.[1] This results in an estimated net addition of 72.9 million pounds of refrigerant per year. This estimate compares favorably with one auto manufacturer's estimate that the average mobile air conditioner unit uses the equivalent of three full charges during its useful life, i.e., one initial charge and two replacement charges.[29]

Nonrecoverable basic leakage resulted in an estimated 6.8 million pounds of refrigerant emissions.[1] Potentially preventable leakage due to design and servicing-related procedures was responsible for an estimated 42.8 million pounds of refrigerant emissions.[1] Finally, it was estimated that 21.3 million pounds were lost during the disposal of scrapped units.[1] This results in 70.9 million pounds of refrigerant emitted into the atmosphere in 1973. The net result is an increase of 2 million pounds of refrigerant per year, based on 72.9 million pounds added and 70.9 million pounds emitted.

The estimated 70.9 million pounds of refrigerant emitted by mobile air conditioning is 33.3% of the total emissions of chlorofluorocarbons used in refrigeration applications. If the refrigeration applications which exclusively use R-22 are eliminated from consideration, then mobile air conditioning accounts for 43.8% of the chlorofluorocarbon emissions of interest in this study. In either case, mobile air conditioning is the largest chlorofluorocarbon emission source among the refrigeration applications.[1]

The overall estimate for refrigerant usage is probably still representative of current initial and replacement charging practices. Although the amount of refrigerant used for new unit charges has declined along with the decline in automotive production recently, this has probably been offset by a rise in replacement usage as people utilize mobile air conditioning for a longer time before salvaging vehicles. A number of auto salvagers estimated that only 25 to 50% of the cars with air conditioning still have a charge when scrapped.[40] Therefore, the published estimate of refrigerant lost at disposal[1] would be reduced by about 10 million pounds.

The evaluation of chlorofluorcarbon emission control in mobile air conditioning end-product applications presented in this section consists of data acquired from various levels of the industry. Information sources include automobile manufacturers, add-on system manufacturers, component suppliers, parts suppliers, material suppliers, installers and servicers of mobile air conditioner units, suppliers of equipment which might be used to recover and/or recycle refrigerants, and trade organizations. The following subsections present an evaluation of emission sources, service practices, and methods which might be employed to reduce emissions through hardware improvements, changes in maintenance procedures, and recovery and recycling systems.

Emission Sources

A typical mobile air conditioning system is shown in Figure III-3. This system consists of a compressor mounted on, and driven by, the vehicle engine, a condenser, a combination filter-dryer-receiver unit, an expansion valve, and an evaporator. Most system components are connected by metal tubes and fittings. However, flexible hoses are used to connect the compressor to the system and isolate engine vibrations.

The sources of chlorofluorocarbon emission can usually be divided into two groups: (1) minor leaks which cause the air conditioning system to operate progressively less efficient because of the gradual loss of the refrigerant charge, and (2) major leaks which result in the complete loss of the refrigerant charge in a short period of time and cause the system to cease operation.

From discussions with numerous manufacturers and service companies, the following sources of leakage (and their magnitudes) were commonly quoted. The minor leaks which most frequently cause refrigerant losses and eventual servicing of the mobile air conditioning system are:

a. The compressor shaft seal

b. Hose permeation

c. Compressor gaskets

d. Fittings

Major leaks which occasionally occur and necessitate immediate servicing of the system are caused by:

a. Auto accidents

b. Hose bursts (due to abnormal operating conditions)

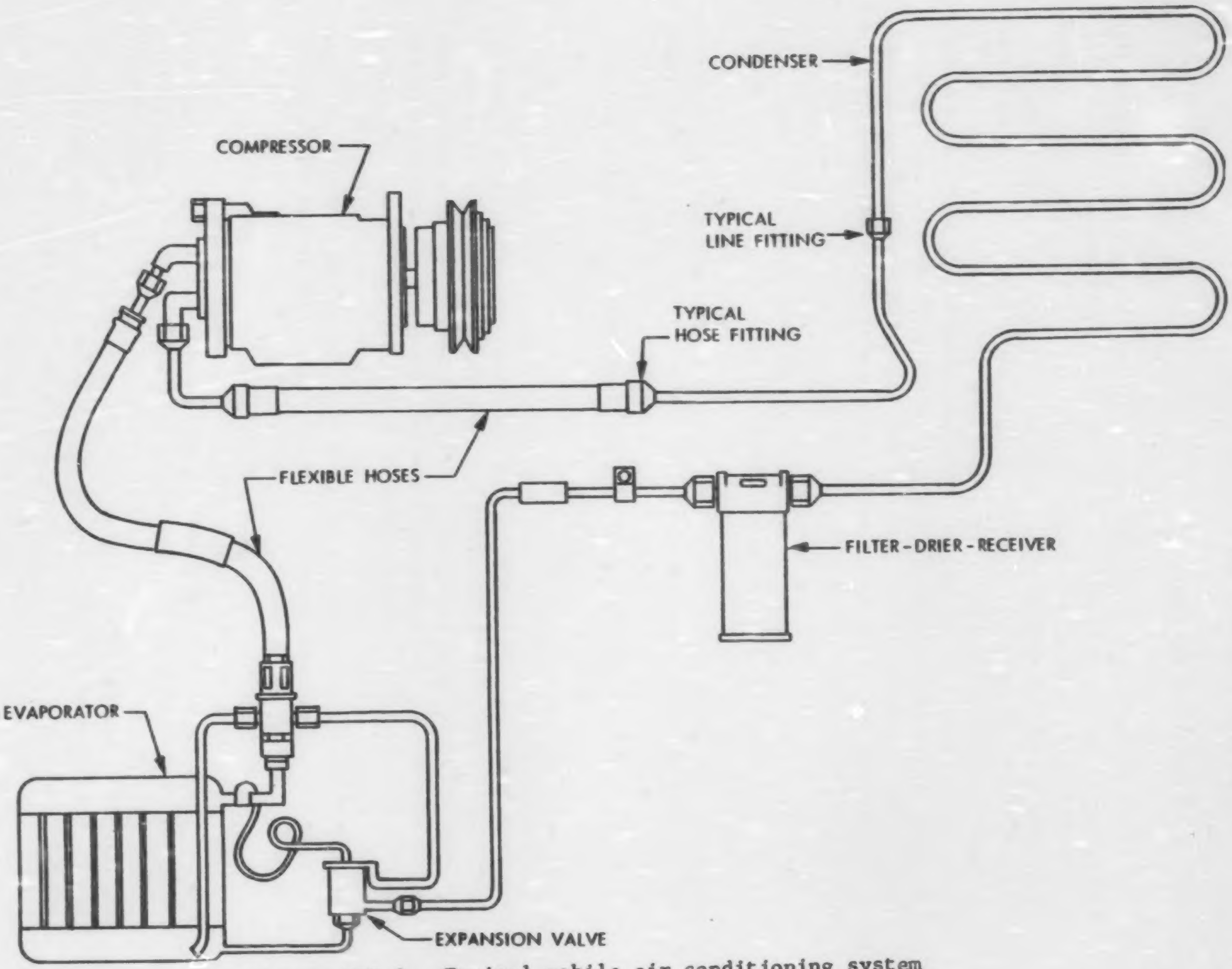

CONDENSER
COMPRESSOR
TYPICAL LINE FITTING
TYPICAL HOSE FITTING
FLEXIBLE HOSES
FILTER-DRIER-RECEIVER
EVAPORATOR
EXPANSION VALVE

Figure III-3. Typical mobile air conditioning system

c. Fatigue of metal lines

d. Compressor failure

Although the major leak sources result in the complete loss of the refrigerant charge, they are relatively rare occurrences, whereas all mobile air conditioners experience one or more of the minor leak sources. Consequently, it is felt that the cumulative total emissions from the minor sources are probably many times the total from the major sources. Also, the major leak sources are largely unpredictable and therefore difficult to eliminate by design or material changes. The minor leaks, on the other hand, are well-known emission sources which could be quite predictable although little quantitative data were found. The remainder of this subsection presents a qualitative analysis of the emission sources and quantitative data which were obtained.

Shaft Seal - The compressor shaft seal is the most frequently mentioned leak source although the exact magnitude of the leakage from the shaft seal is largely unknown. Engineering specifications for the shaft seal vary from 1/2 oz per year at one compressor manufacturer[28/] to 5 oz per year at one automotive manufacturer.[29/] Detection of leakage during assembly of the system is made by using electronic leak detectors or by doping the refrigerant with a small amount of helium and using a helium detector.

The compressor shaft seal actually consists of two seals--one dynamic rotating seal and one static nonrotating seal. The dynamic seal consists of a set of rubbing elements, one of which is mounted on and rotating with the compressor shaft and the other which is a nonrotating element mounted in the compressor housing and spring-loaded against the rotating element. One rubbing element is typically a lapped cast iron plate while the other rubbing element is a ceramic material such as aluminum oxide or sintered carbon graphite. The ceramic element must be impregnated with a nonpermeable material to prevent diffusion of refrigerant through the element. The static seal is usually an O-ring which is mounted between the nonrotating element and the housing to allow axial movement of the element while preventing leakage between the housing and the nonrotating element. Leakage may occur past either the O-ring or the rubbing interface, although the rubbing interface is usually thought to be the worse of the two.[36/] Another source felt that the static seal contributed equally to the total leakage.[35/] Permeation through the ceramic rubbing element can also be a shaft seal-related leakage source.

Manufacturing tolerances and surface finishes play important roles in the seal effectiveness. The cast iron plate must be lapped flat and typically a flatness of 23×10^{-6} in. is specified.[28] Also, over 800 types and grades of ceramic material are available for the other rubbing element. Therefore, proper selection of the material is important.

Operating conditions are important, particularly during the winter months when the refrigeration oils can gum up the surfaces of the rubbing elements if the system is not operated periodically. This causes high friction and temperature to be generated when the sysetm is started, resulting in seal damage.

Hoses - Permeation of refrigerant through the hoses used in mobile air conditioners is difficult to evaluate although several sources indicated that the losses are a significant source of emissions. One auto manufacturer specifies hose permeation rates to be less than 0.1 oz per foot per year.[29] Therefore, the average mobile air conditioning system which may have 10 ft or more of hoses could account for only about 1 oz per year of leakage. Several other believe this value to be too low.

One hose commonly used in automobile air conditioners is lined with butadiene-acrylonitrile copolymer elastomer, which is resistant to R-12 and to oil. The outer layers of this hose are usually another elastomer (polychloroprene), chosen for its weather and abrasion resistance. Data published by Du Pont for a 1/2 in. I.D. hose of this material indicates negligible leakage at 75°F (24°C), 0.3 oz per foot per year at 100°F (38°C), 3.5 oz per foot per year at 130°F (54°C), 9.1 oz per foot per year at 160°F (71°C), 16.1 oz per foot per year at 185°F (85°C), and 30.3 oz per foot per year at 220°F (104°C).[30] It should be noted that the vapor pressure of the refrigerant increases from about 90 psia (6.3 kg/cm^2) at 75°F (24°C) to about 524 psia (36.8 kg/cm^2) at 220°F (104°C). From these data it is apparent that the system operating temperature and pressure have a significant effect on the leakage rate and that a weighted mean temperature and pressure would be necessary to accurately predict the actual annual leakage.

Nylon hose has recently been recommended for use as an air conditioning hose and is presently being used on some new car air conditioners. Test data indicate a diffusion rate of 0.5 to 1.6 oz per foot per year when used at a temperature of 180°F (82°C).[31] Table III-3 gives permeation test data for four hose materials when used with refrigerants R-12, R-22, R-500, and R-502.[32] In these tests the nylon liner was 0.025 in. thick and the elastomer hoses were 0.140 in. thick. All test hoses were 0.50 in. I.D. and 18 in. long. A correlation for loss rate per foot per year versus temperature is given in Figure III-4 for NBR, CS, and nylon hoses.

Table III-3. PERMEATION CONSTANTS, OIL PRESENT[32]

Hose type	Refrigerant	Test temperature, K x 10^5 75° F (24° C)	100° F (38° C)	140° F (60° C)	180° F (82° C)	220° F (104° C)
CSM	12	D[a]	D	D	0.889	3.52
CSM	22	D	3.86	5.03	5.80	7.1[b]
CSM	500	D	D	0.338	1.81	3.92
CSM	502	D	D	0.40	1.29	1.72[b]
Neoprene	12	D	2.34	3.59	5.08	5.92
Neoprene	22	4.4	5.26	7.83	7.95	9.06[b]
Neoprene	500	1.1	2.28	4.46	5.12	7.30
Neoprene	502	0.641	1.17	2.57	3.07	3.06[b]
NBR	12	D	0.162	1.02	1.94	2.53
NBR	22	114.5	U[c]	U	U	U
NBR	500	1.14	5.66	4.08	6.0	4.45
NBR	502	6.57	9.05	8.50	9.10	5.62[b]
Nylon	12	D	D	0.012	0.0223	0.0225
Nylon	22	0.434	0.596	0.545	0.63	0.77[b]
Nylon	500	D	0.00903	0.0168	0.0491	0.155
Nylon	502	D	0.143	0.127	0.240	0.292[b]

---

[a] D = Did not get through the preconditioning in 14 days.

[b] A pressure of 800 psia was used in the calculation of the constant for R-22 and R-502. This was justified by the pressure transducer data and extrapolation of the refrigerant pressure versus temperature graph beyond the critical point.

[c] U = Unmeasurable (too fast).

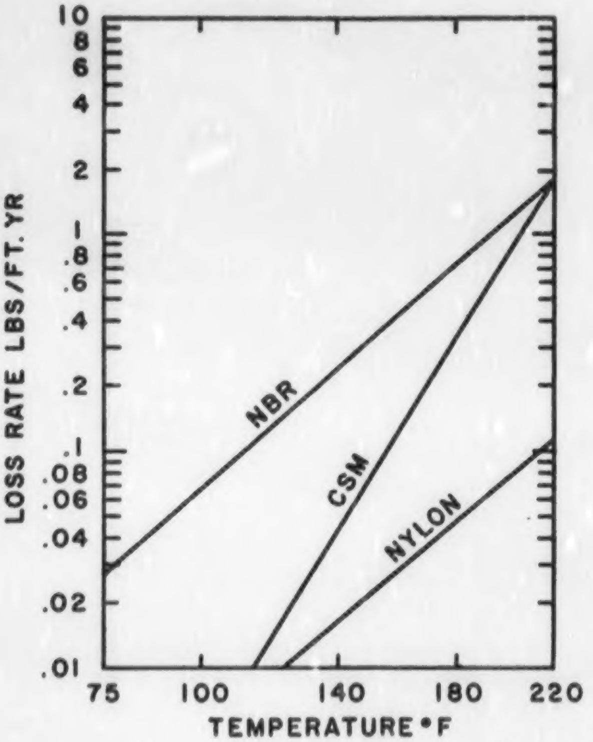
CSM = Chlorosulphonated polyethylene (43% chlorine content)
NBR = Nitrile rubber

Permeation constants were calculated at each test temperature for each combination of hose type and refrigerant using the following equation:

$$P_r = \frac{KAP}{t} \rightarrow K = \frac{P_r t}{AP}$$

where: P_r = Observed loss rate, g/day
A = Inside surface area of hose (28.25 in.^{2})
P = Absolute refrigerant pressure (saturation pressure)
t = Thickness of hose liner (0.025 in. for nylon and 0.140 in. for all others)
K = Permeation constant, g-in/day-lb_f

Source: Freon® Product Information RT-51, E. I. du Pont de Nemours and and Company, Inc.



Source: Freon® Product Information RT-51, E. I. du Pont de Nemours and Company, Inc.[32]

Figure III-4. R-12 (with oil) loss rate versus temperature

A hypothetical calculation for a system containing R-12 in NBR hoses and operated during typical conditions for a year is given in Table III-4. From this calculation it is shown that the majority of the refrigerant permeation loss in average cars occurs when the car is not operating and the hoses are at ambient temperature. Although the permeation rate is higher when the car is operating, the car is parked many more hours than it is operating. The loss during air conditioner operation is less than 40% of the total loss.[32]

Gaskets and Seals - Elastomers are extensively used for gaskets and seals in mobile refrigeration compressors. The refrigerant and refrigerant-oil mixtures can cause swelling of the elastomer material and extraction of plasticizers and other agents used in the elastomer formulation. Improper material selection can cause weakened or diminished mechanical properties which may lead to leakage by diffusion or improper fit. Poor design or installation may also contribute to an improper fit that can cause leakage. Data on the magnitude of the leaks

Table III-4. R-12 CALCULATED LOSS RATE FROM AUTO AIR CONDITIONING SYSTEM, NBR HOSE[32] WITH R-12 AND OIL

	Avg. hose temp. (°F)	200 Hr/year car operating AC operating (lb/year)	Avg. hose temp. (°F)	400 Hr/year car operating AC not operating (lb/year)	Avg. hose temp. (°F)	8,100 Hr/year parked (lb/year)
Discharge hose	220	0.053	100	0.007	50	0.029
Liquid hose	130	0.013	100	0.007	50	0.029
Suction hose	60	0.001	100	0.011	50	0.043
Total		0.067		0.025		0.101

Grand total = 0.19 lb/year loss

Source: Freon® Product Information RT-51, E. I. du Pont de Nemours and Company, Inc.

through elastomer sealed or gasketed joints is unavailable. Several sources indicated that the relative magnitude of leaks at elastomer sealed or gasketed joints is less than at shaft seals or through hoses. One compressor manufacturer has a specification for a leakage rate that does not exceed 1/4 oz per year from any given point,[28/] while one auto manufacturer's specification is 1/2 oz per year from any one point.[33/] Measurement methods used to check the finished products against the specifications were not revealed.

Fittings - Several sources mentioned line fittings as potential leak sources. However, most believed that properly selected and installed fittings cause a minimum of leakage. Adherance to installation torque specifications is the most important method to minimize or eliminate leaks at fittings according to one source,[33/] while periodic retightening checks to detect fittings loosened by vibration was recommended by another.[34/] In either case, it was acknowledged that fittings can and do leak, but the leakage rate or contribution to total refrigerant emissions is unknown.

Hose fittings are similar to line fittings except that one of the joined sections is an elastomer refrigerant hose. Although the metal to metal connections of the fittings are no worse than other line fittings, the portion of the fitting connected to the hose is a problem area and frequent emission source. These fittings normally use a crimped assembly technique to join the hose and fitting and must form a good mechanical joint in addition to containing the refrigerant. Typical leakage rates or the contribution to total emissions is unknown.

The cumulative losses from all minor leak sources is estimated by various sources to range from several ounces to 1/2 lb or more per year for an average mobile air conditioner unit.

In addition to the annual leakage from the minor leak sources, some mobile air conditioning units develop failure which cause the entire charge to be lost.

Accidents

Automobile accidents can cause the loss of the air conditioner refrigerant charge by rupturing a portion of the system. The most frequent source is the condensor coil which is mounted in front of the radiator and is quite vulnerable in any accident with front-end damage. Metal connecting lines can also be bent and broken to release the charge. Although total release of charge is an obvious source of refrigerant emissions, no statistical data were found that give the number of accidents resulting in refrigerant loss. Several auto salvage yards indicated that only

25 to 50% of the air-conditioned cars scrapped have a refrigerant charge remaining and that many of the cars without charges have been involved in accidents.[40]

Hoses - Hose bursts, which occur occasionally and cause a complete loss of the refrigerant charge, can result from a number of causes such as improper material selection, malfunction of some other component in the system which results in excessive internal pressure, damage from outside sources, vibration, deterioration with age, and manufacturing or assembly defects. Design and manufacture-related causes are usually quickly discerned and remedied, whereas the use and operation-related hose failures are difficult to predict or eliminate.

Line Fatigue - Fatigue of metal lines is a vibration-related failure that can also occur and result in the complete loss of the refrigerant charge. According to repair shops, this type of failure seems to be design-related; a few certain makes, years, and models of automotive air conditioner systems are prone to this type of failure, while most others are rarely affected.

Compressor Failure - Occasionally the malfunction of the mobile air conditioning compressor will result in the cracking of the compressor case, head, or other components; this then allows the complete loss of a refrigerant charge. This type of failure is believed by some sources to usually be caused by insufficient lubrication which in turn may be caused by the loss of oil along with refrigerant at other leakage points in the system.[34] This type of failure may also result from the mechanical failure of the compressor components. The number of compressor failures which cause the emission of the refrigerant charge is not known, but is estimated to be relatively small.

In addition to the emission sources just discussed, significant quantities of refrigeran[illegible] vented to the atmosphere during servicing and repair of mobile ai[illegible]itioning systems.

Service Practices

Present maintenance and service practices for mobile air conditioning systems were found to vary greatly. Most minor leaks are tolerated by the unit owner until the system performance declines (cold air output diminishes) and necessitates the repair of the system and/or the addition of refrigerant. Usually the latter is chosen and refrigerant is added to restore the system performance without any repair being undertaken.

Frequently the refrigerant is added by the vehicle owner using readily available charging kits and small 13 to 16 oz cans of refrigerant. The charging kit consists of a flexible hose with a Schrader valve on one end and a valve assembly which attaches to and pierces the refrigerant can on the other end. The charging kit sells for $3 to $6 and the refrigerant sells for about $1.50 per can. If properly used, it allows safe and economical replacement of lost refrigerant. If improperly used, charging kits can be dangerous and may explode if connected to the wrong service valve on the air conditioner system. In either case, repairs which may be needed are delayed and chlorofluorocarbon emissions will continue to occur from the system.

If the unit owner does not use a do-it-yourself charging kit, he will most likely take the unit to a service station or general repair shop. About 50% of the service stations and most general repair shops engage in some form of mobile air conditioner service work. Many of these simply add refrigerant and check for leaks. The refrigerant is usually added through a manifold-gage set which allows monitoring of pressures at various points in the air conditioning system and aids in diagnosis of system problems. Leaks may be detected by observing pressure changes on the manifold gages, visual observation of oil escaping with the refrigerant at leak points, or by using leak detectors such as halide torches, if they are available. Many of the service stations and general repair shops engaged in air conditioning servicing only add refrigerant and perform diagnostic checks while offering little, if any, additional air conditioning service. Also there are many shops which purge partially charged systems before recharging the system to the factory specifications. This procedure only increases the emission problems. The more difficult repairs are referred to large dealer service shops and air conditioning specialty shops.

The larger dealer service shops and air conditioning specialty shops tend to have sensitive leak detectors and the specialized equipment necessary to offer complete and competent repair service. Consequently, those shops receive the more difficult cases which are not repairable by the unit owner or general repair shops and service stations. Prior to any servicing which requires opening of the system, all remaining refrigerant is blown into the atmosphere without any attempt for recovery or recycling of the used charge. Many of the systems which must be opened still contain all or nearly all of their refrigerant charge. Failures of components such as the expansion valve, or compressor jams, or plugging of internal passages within the system require opening of the system for repair and result in large quantitites of chlorofluorcarbons being released into the atmosphere. The frequency of these types of failures and the resultant emissions during servicing are not known, but the intentional release of refrigerant to the atmosphere is believed to be a significant emission source.

Methods of Reducing Emissions

This section presents and examines the technical feasibility, cost, and effectiveness of reducing or eliminating environmental contamination from mobile air conditioning systems by improving hardware, by improving operating and maintenance practice, and by instituting recovery and recycling programs.

Hardware - Prospective hardware changes fall into three general categories: (1) improvement of selected parts and components, (2) general redesign of the complete system, and (3) radical redesign of the system.

Improvement of selected components such as the compressor shaft seal, flexible hoses, gaskets and fittings, which are responsible for large quantities of refrigerant emissions when their cumulative effects are considered, would result in the most immediate benefits.

The compressor shaft seal presently contributes approximately one dollar to the $30 to $40 cost of the total compressor. Shaft seals have been greatly improved since the introduction of mobile air conditioners, and seal manufacturers believe that present seals represent the near ultimate state of the art. Surface finish, porosity, and tolerance of the seal components are the primary concerns of the seal designer. One seal component manufacturer stated that there are 800 to 900 types and grades of seal materials available to the designer, but the cost variation between materials is probably only plus or minus 10%.35/ Of greater influence on the seal cost are the physical configurations of the seal components and the manufacturing tolerances which can cause up to 500% variation in the cost of the finished seal. One seal manufacturer reported they use random sample quality control techniques such as given in MIL-Std 105 to determine the acceptance quality level of each lot rather than inspect each finished seal.

It appears that tighter tolerances and more rigorous inspections would reduce subsequent emissions. This would cause higher reject rates and consequently increase the cost of the acceptable seals by a factor of 2 to 3 if acceptable output were cut in half. One manufacturer is reportedly developing a phenolic material to replace ceramic and sintered material now in use with the hope of eliminating porosity problems.36/ An estimated cost of a seal made from this material was not available. In general, the seal manufacturers concede that a leak-proof compressor shaft seal is not possible.

Prospective hose changes fall into two groups: (1) improved materials for substitution in existing elastomer hose designs, and (2) replacement with flexible metal hoses. One industry source believes that

Teflon® -lined hoses would have a very low leak rate and retain the vibration isolation advantage of present system designs which utilize elastomer hoses. Unfortunately, the source also stated that reliable fittings for use with Teflon® -lined hoses were not available for the pressures and temperatures encountered in mobile air conditioner systems.[34/] No permeation data were obtained for Teflon® -lined hoses although they are used for many applications where chemical resistance is important. Development of suitable fittings should be technically feasible but costs are unknown. Development of a multilayer hose might be a feasible alternative if the Teflon® could be sandwiched between layers of conventional hose materials to serve as a refrigerant barrier. It is estimated that such a hose would probably cost 50 to 100% more than presently used hoses. Increasing the wall thickness of present hoses might also reduce refrigerate permeation and would increase costs in proportion to the thickness increase.

Flexible metal hoses are a frequently mentioned alternative to conventional hoses. These were reportedly used on one make of car in the 1950's, but were quickly abandoned because of vibration-induced fatigue cracks that caused loss of refrigerant. It is not known if any air conditioner manufacturers have evaluated flexible metal hoses recently, but improvements in metal hose designs--particularly in the aerospace programs--might make them a candidate for reconsideration. Cost is also a hinderance to the introduction of flexible metal hoses. A typical 4 ft length of elastomer hose with conventional fittings costs about $10, a similar hose with special fittings or other features costs in the $20 to $30 range while flexible metal hoses would cost in the $35 to $45 range.[41,42/] Since mobile air conditioners contain at least two flexible hoses, the cost increase due to flexible metal hoses would probably be $30 to $60 per unit.

Many prospective component changes could be retrofitted to existing mobile air conditioners when making repairs or they could be integrated into present production systems with a minimum of difficulty once substitute parts are developed and made available. General redesign of the system, however, may not be as easily incorporated into present systems.

Changes which might be included in a general redesign of the system where the major components remain relatively unchanged are: (1) the addition of isolation valves; (2) reducing the number and improving gasketed compressor joints; and (3) changing from mechanical joints to brazed joints when possible.

The present mobile air conditioner systems generally do not contain isolation valves, although one automobile manufacturer, which uses precharged air conditioner components, has valves incorporated into some of the line connections. The addition of isolation valves would enable service repairmen to repair a portion of the system without venting the entire or remaining refrigerant charge into the atmosphere. As a minimum, two valves could be installed to isolate the compressor and additional valves would make isolation of other major components possible. The estimated increased costs are $1 to $2 for each valve plus a similar amount for labor. One possible problem with isolation valves is that the valve stem and fittings could become additional leak sources.

Reducing the number and improving gasketed compressor joints would be a technically feasible method to reduce emissions; however, no design studies have been made. This would require significant redesign of the compressor unit and tooling changes. Generalized compressor studies by one automotive engineer indicate that $20 to $30 million would be required for retooling, with a minimum of 3 years to production.29/ These figures assume that shaft seals would be allowed.

Changing mechanical joints to brazed joints would eliminate fitting leaks, although it may pose some assembly and repair problems. In general, brazed joints have been found to be more reliable and to cost less than mechanical fittings when used on household refrigerators and freezers. This might also apply to mobile air conditioners. However, household appliances are brazed before being installed in their cabinets while mobile air conditioners would probably have to be brazed after installation in their vehicle. Additional study and redesign would need to be undertaken to determine the feasibility of using brazed joints to connect mobile components.

One automotive engineer summarized his comments on the improvement of existing systems as follows:

> "In the short term, modest reductions in leakage appear obtainable through increased leak detection and quality control efforts during manufacturing and assembly. In the long term, design revisions to reduce leakage may be feasible (reduced number of fittings, better hose materials, revised manufacture and assembly procedures, and better leak detection equipment). These efforts would increase manufacturing costs."37/

These comments were also representative of other contacts in the automotive industry.

The most often mentioned radical system redesign is the development of a hermetic mobile air conditioner. One automotive engineer commented that a hermetically sealed system would require a direct current electric motor developing up to 7 h.p. to compete with today's cooling rates. The power generation equipment to supply this electric motor and the motor itself would pose a tremendous packaging problem without a major vehicle redesign.[29] Another automotive engineer had the following comments:[37]

> 1. "The addition of an electric motor and associated power conversion equipment and the increased size of the alternator to provide the required A/C power would impose significant weight and cost penalties."
>
> 2. "To provide equivalent cooling performance, the A/C power requirement would be approximately quadrupled due to the two additional stages of energy conversion required between the engine shaft and the compressor, and the efficiency of power conversion equipment. It thus seriously negates the mandated requirement of improving fuel economy of our products."

A reply from a compressor manufacturer indicated that a hermetic unit is technically feasible, that it would add about $150 to the present cost of automotive air conditioning, it would allow the unit to be moved away from the engine compartments high temperature environment, and that some research and development work on hermetic automotive units had been undertaken.[43]

Further investigation into the power requirements show that present automotive alternators generate the electrical equivalent of 3/4 to 1-1/2 h.p. Therefore, an electrically driven mobile air conditioner would require an alternator with 5 to 10 times the electrical output of present alternators. Although the physical size and cost would probably not be increased at the same rate as power output, the cost increase to the consumer would still be substantial. The retooling cost would be much greater than the $20 to $30 million estimate reported for generalized compressors of conventional design.

Another type of hermetic drive available would be magnetic couplings.[44] This type of drive uses rotating magnets on the outside of a thin-walled tube to drive similar magnets on the inside of the tube and essentially transmit power through the tube wall. The size and cost of a system to drive mobile air conditioner compressors is not known. The refrigerant pressure on the inner tube surface may limit the feasibility of this type of hermetic drive.

Operating and Maintenance Practices - Changes in operating and maintenance practices generally fall into two groups: (1) owner-oriented changes, and (2) service shop-oriented changes. The owner-oriented changes are increased education to operate the system periodically during the winter months and elimination of do-it-yourself changing kits. Elimination of the do-it-yourself kits was recommended by a number of sources because recharging of a nonperforming or leaking system merely prolongs the problem.

Mobile air conditioner manufacturers recommend that their units be operated periodically during the off season to prevent the shaft seal from drying out or gumming up. Failure to do so causes high friction and temperatures when the system is first started the next cooling season. This can cause damage to the shaft seal and result in premature failure and excessive emissions. To eliminate the need for periodic starting, one automobile manufacturer has introduced compressors which rotate the compressor shaft and seal whenever the engine is running.

The service shop-oriented changes are the elimination of unnecessary system purges and recharging, and better leak detection. Since the most frequent symptom for needed air conditioning service is a low refrigerant charge, many air conditioner locations simply recharge the system, much as the do-it-yourself owner would do, and perform no repairs to remedy the problem. Some servicers reportedly purge any remaining charge from the system prior to recharging. Indiscriminent purging and recharging should be eliminated.

Many servicers of mobile air conditioning equipment do not have leak detection equipment available or have only moderately sensitive detectors such as halide torches. Wide spread use of the more sensitive electronic leak detectors or mixing a dye (e.g., Dytel®) in the refrigerant would aid in better leak diagnosis and help prevent the recharging of systems with excessive leaks. Electronic leak detectors with sensitivities suitable for detecting small leaks cost in the $1,000 to $2,000 range. Less sensitive units are available for as little as $100.

Recovery and Recycling - Presently, very little recovery equipment is available. No United States automobile manufacturer attempts to recover refrigerant from the defective systems found on the production lines nor do any service shops prior to servicing systems in use.

One assembly plant in Mexico reportedly uses a 7-1/2 h.p. condensing system to remove refrigerant from defective air conditioners prior to reworking.[38] The unit cost is about $18,000 and has been in use 3 to 4 years.

According to one automotive engineer:[37]

> "Recovery and recycling of R-12 at the manufacturing plant appears feasible. Aeronutronic-Ford Corporation has designed and is in the process of installing a recovery and recycling system to be used in conjunction with leak test facilities for refrigeration system components."

Smaller systems suitable for refrigerant recovery in service shops have been estimated by a number of sources to cost from $300 to $1,000 or more, depending upon the degree of recovery required and the size of the systems and components used for recovery. Several simple systems are possible such as purging into an evacuated tank or using a chilled tank. These are not feasible for high volume service shops or production lines and would require the eventual transfer of the collected refrigerant to other tanks.

Nearly all sources contacted would not recommend the direct recycling of recovered refrigerant back into air conditioner systems because of the possible contamination which might be present and the unknown percentage of oil in the recovered mixture. Distillation of the used refrigerant would be required before it could be acceptable for reuse. Distillation of R-12 used in mobile air conditioners is probably beyond the capabilities of most service shops; they would have to rely upon an outside distilling service. According to an industry source, companies are reported to purchase used refrigerant for distilling, but no financial details are known.[46/]

One refrigerant producer has designed and is offering for sale an OEM refrigerant reclaimer system capable of removing and reprocessing up to 90 lb/hr of refrigerant for reuse. The cost of this system is reported to be $7,500 without storage tanks.[24/]

Auto salvagers face recovery problems similar to those encountered by service shops. However, since salvagers would have no potential for recycling refrigerant, a market or approved disposal system for the recovered refrigerant would be needed.

One automotive engineer summarized refrigerant recovery with the following comments:[37/]

> "Refrigerant could be recovered during service and when a vehicle is being scrapped with technology now available. The recovery and storage equipment is not available, however, and would require time for development. An economic incentive may be necessary to promote the use of recovery techinques during service, repair, and scrap operations."

These comments were also typical of other contacts throughout the automotive, service, and salvage industries; however, since recovery and storage equipment are presently available, but not widely used, the time required for development of new systems would not be needed.

CHILLER SYSTEMS

Chiller systems are often referred to as "secondary refrigeration systems" because one refrigerant is used to cool a second refrigerant, which in turn is used to cool the building or enclosure. These units are large scale systems used in the air conditioning of industrial or commercial buildings. Their use in these applications, as opposed to a single refrigerant system, is because it is easier and more efficient to pump a cooled liquid (water or brine) long distances than it is cold air.

A published report stated that in 1973, a total of 271,000 chiller units were in operation in the United States or had been shipped.1/ Of this number, about 54,000 were centrifugal compressor chillers and 217,000 were reciprocating compressor chillers. The importance of these systems with respect to chlorofluorocarbon emission lies not in the total number of units, but rather in the quantity of refrigerant charge per unit. According to the A. D. Little report, the average charge per centrifugal unit is 2,500 lb while a reciprocating system holds an average of 350 lb.1/ A manufacturer has recently estimated the average charge per centrifugal unit at 1,635 lb and a reciprocating system at 137 lb.47/ These two systems accounted for an estimated 33.9 million pounds in annual emissions or about 24% of the total emissions in the area of refrigeration and air conditioning.1/ These latter two figures include contribution by R-22 in addition to the refrigerants of interest to this study.

The major manufacturers of chiller units are Carrier, Trane, York, Westinghouse, and Airtemp (Fedders). These five companies control about 80% of the large unit market.45/

In the following parts of this subsection, discussions will be devoted to the basic system design, sources of refrigerant emission, and potential methods of emission control.

Basic System Design

The basic difference between reciprocating chillers and centrifugal chillers is in the type of compressor being used and, hence, the refrigeration capacity of the two systems. Reciprocating compressors operate on the principle of a piston traveling back and forth in a cylinder. These units are used in applications up to approximately 100 tons refrigeration capacity. Reciprocating compressors can be used for capacities greater than 100 tons, but above this level the centrifugal compressors are more efficient and are commonly employed. Centrifugal compressors, in which an impeller rotates within a housing, draws in vapor and discharges it at a high velocity causing compression by centrifugal force.

In terms of refrigerant usage, the older, open-type reciprocating compressor systems are high pressure units, employing essentially 100% R-12. A vast majority of the new reciprocating systems presently on the market are hermetic or semihermetic units using R-22.[18] For centrifugal compressor systems, lower tonnage units (up to 1,000 tons) commonly use R-11; intermediate tonnage (1,000 to 5,000) units use either R-12 or sometimes R-114; high tonnage (5,000 to 15,000) systems use R-22 as the refrigerant. These tonnage figures are approximate and should not be interpreted as a clear line of demarcation. At times, R-113 and R-11 are employed in hermetic centrifugal chiller systems having 80- to 500-ton capacity.[8,45]

As would be expected, the refrigerant capacities of these units varies considerably with the tonnage. A 20-ton reciprocating unit has a primary refrigerant charge of about 40 to 50 lb, whereas a 60-ton unit holds approximately 150 to 200 lb. For centrifugal chillers, a 100-ton unit has a refrigerant charge of about 400 to 500 lb. Because of improvements in system design, the refrigerant charges of new centrifugal units have been reduced to about 60% of that of the older units.[45]

Aside from the secondary refrigeration system, the design of chiller units is basically the same as that for the vapor compression cycle used in other air conditioning systems, but the scale is much larger. A simplified composite design for a chiller unit is shown in Figure III-5.

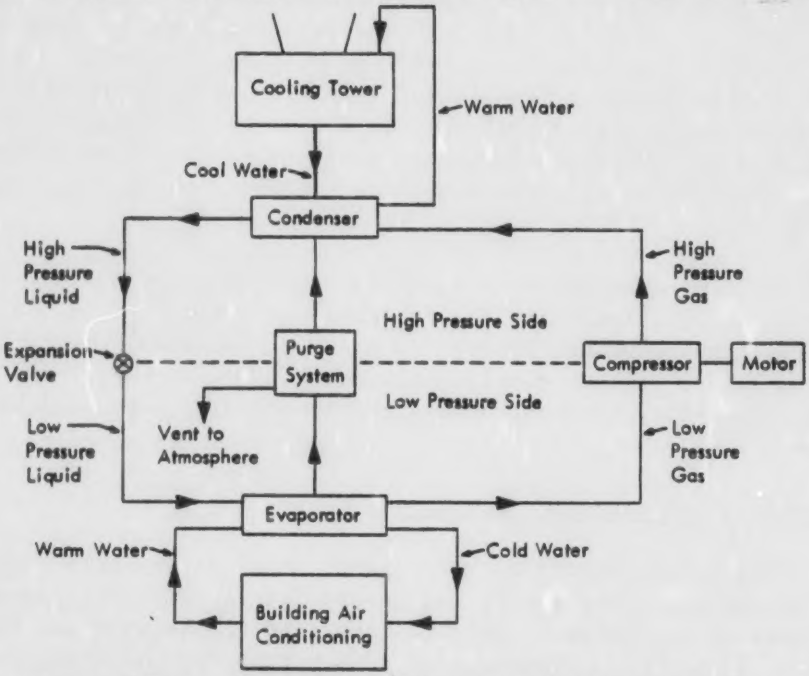

Cooling Tower
Warm Water
Cool Water
Condenser
High Pressure Liquid
High Pressure Gas
High Pressure Side
Expansion Valve
Purge System
Compressor
Motor
Low Pressure Side
Vent to Atmosphere
Low Pressure Liquid
Low Pressure Gas
Evaporator
Warm Water
Cold Water
Building Air Conditioning

Figure III-5. Composite diagram of chiller systems

As shown in the figure, the primary refrigerant (chlorofluorcarbon) in these chiller systems is used to cool a secondary refrigerant, water or brine, which is then circulated to cool the building or enclosure. This figure is a composite in that it does not represent a specific chiller system but contains components found in both low and high pressure systems. For example, purge systems are necessary only for a low pressure (R-11 or R-113) centrifugal chiller system so for a high pressure (R-12) unit, the purge system would be absent. An air cooling system can be used instead of a cooling tower. As shown, the compressor-motor arrangement implies an open-shaft reciprocating or open-drive centrifugal system. In a semi-hermetic or hermetic system, the compressor and motor would be combined into a single unit and not separated as shown. The average lifetime of a chiller system, either reciprocating or centrifugal, is about 20 years.[45,46]

All reciprocating compressor systems are high pressure units. In the past, R-12 was used almost exclusively in these units. It has been stated that there is no valid reason why a reciprocating compressor chiller unit needs to use R-12; in fact, almost all of the new units employ the use of R-22 except possibly for low temperature applications. R-22 provides approximately 60% more cooling capacity than an R-12 unit.[18] Existing R-12 units could, technically, be converted to R-22 units. One source states that this conversion would involve installing a completely new condensing unit, changing all in-line pressure valves, expansion valve, and other parts to accommodate the higher pressures employed in a R-22 system. Such a conversion would be costly, but it is technically feasible. For a small 5-ton unit, converion would cost approximately $2,000 per unit; for a 7.5-ton unit, approximately $3,000.[46] Another source states that the conversion can be accomplished more simply and at a lower cost.[18] Multiple small units are often found in office buildings, etc., to provide more control over the cooling than one large unit.

Chiller manufacturers generally construct the basic hardware of their systems, including the raw castings, oil pumps, motors, and other fabricated equipment. Typical components purchased from subcontractors or suppliers include compressors, relief valves, electrical controls and components, gaskets, seals, refrigerant, and numerous small hardware items.[45]

Sources of Refrigerant Emission

The major sources of refrigerant emission in chiller systems can be attributed to primarily two generalized areas: (1) leakages due to mechanical or equipment malfunctions, and (2) service and repair operations. Of the total refrigerant consumption for these two purposes, it has been estimated that approximately 75% of the total is used to replenish refrigerant lost due to leakage and 25% is consumed to replace fluid discarded during service and repair operations.[46] A published report has stated that 75% of the total refrigerant leakage (excluding disposal) in centrifugal and reciprocating chillers is preventable through relatively minor modifications to current equipment design or service procedures and 25% of the leakage is due to nonrecoverable leakages.[1] The report provides no clarification with respect to which leakages are considered to be preventable or nonrecoverable.

An industry source has stated that one manufacturer has provided data on leakage rates for a centrifugal chiller.[47] The manufacturer stated that for R-11 systems, about 1.1% of the charge is lost due to minor leaks (joints, components, etc.) and approximately 0.2 to 1.0% is lost due to shipping problems, damage to refrigerant lines during operation or repair, and deliberate release to the atmosphere. For high pressure R-12 systems, the leakage rate due to minor leaks is approximately 3.1% and ranged from 0.25 to 1.3% for leakage due to shipping, line damage, and deliberate release. The manufacturer was unable to estimate how much refrigerant is lost to the atmosphere when the machine is opened for service.

Refrigerant emissions and equipment failure are basically uniform with respect to geographical location. The midwestern part of the United States, i.e., the Plains States, seems to encounter equipment problems before other geographical areas. Since high humidity has a greater effect on the "load" of a system than temperature, perhaps the combination of high summer temperatures and high humidity are a factor in early failures.[46] One failure that is geographically oriented is with the use of air-cooled condenser systems. In coastal areas, these condenser systems are much more susceptible to corrosion problems, due to the salt water in the air, than in other areas of the country.

Emissions Due to Leakage - The most common service call is due to low refrigerant levels resulting from the leakages to be discussed in this subsection. According to a nationwide refrigeration and air conditioning service company[46] and manufacturers of chiller systems,[45,48] the major sources of leakage in these large systems are as follows:

- Pressure relief valves and rupture discs;
- Purge systems (low-pressure centrifugal units only);
- Compressor shaft seals;
- Gaskets; and
- Miscellaneous minor sources.

Of these types of leakage, pressure relief valves and purge systems, are sources of large leaks, which can result in the emission of significant quantities of refrigerant to the atmosphere with a single malfunction. Line breakages or cracks and leaks through gaskets, seals, and faulty solder joints will emit small quantities of refrigerant at any one time but the continual leakage over a period of time can result in the loss of significant quantities.

Figures III-6 and III-7 are photographs of chiller systems in present usage at Midwest Research Institute (MRI). These systems are for illustrative purposes only and the presence of any tradenames or general recognition of the units is not intended to be an endorsement of a particular product.

Figure III-6 shows typical sources of leakage from a centrifugal chiller system. The sources, designated by numbered arrows, are as follows:

1. Oil dash pot;
2. Gasket on refrigerant loading arm;
3. Pressure rupture disc--vented to the atmosphere;
4. Gasket on refrigerant sight glass;
5. Purge system;
6. Gasket on Venturi chamber;
7. Gaskets on two flanged joints on refrigerant equalizing line; and
8. Hose on the oil return line.

In Figure III-7, the numbered arrows show the potential sources of refrigerant leakage in a reciprocating chiller system. In this illustration, the sources are delineated as follows:

1. Gasket on hand valve;
2. Flange gasket;
3. Gasket on hand valve;
4. Expansion valve;

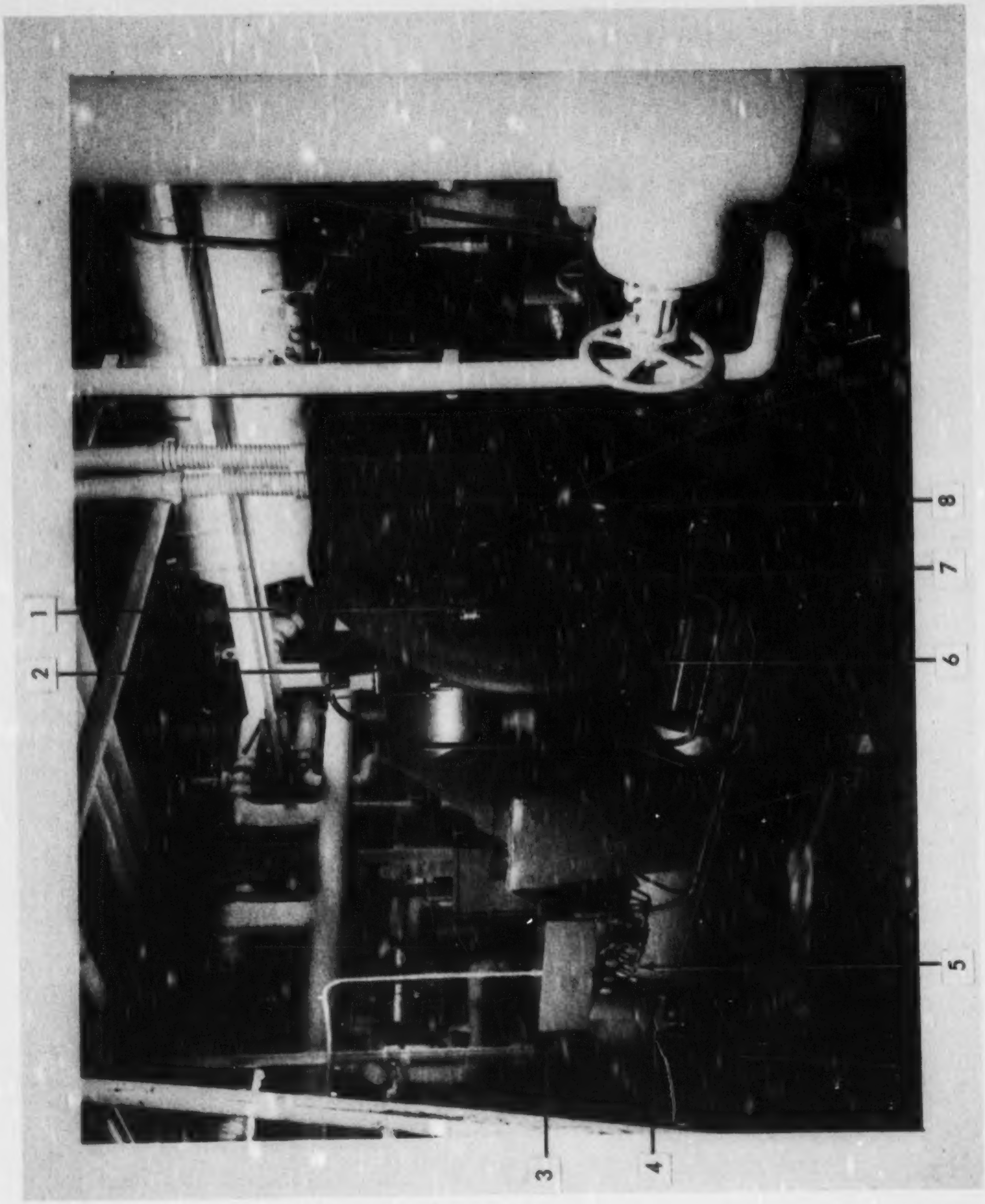


Figure III-6. Centrifugal chiller system

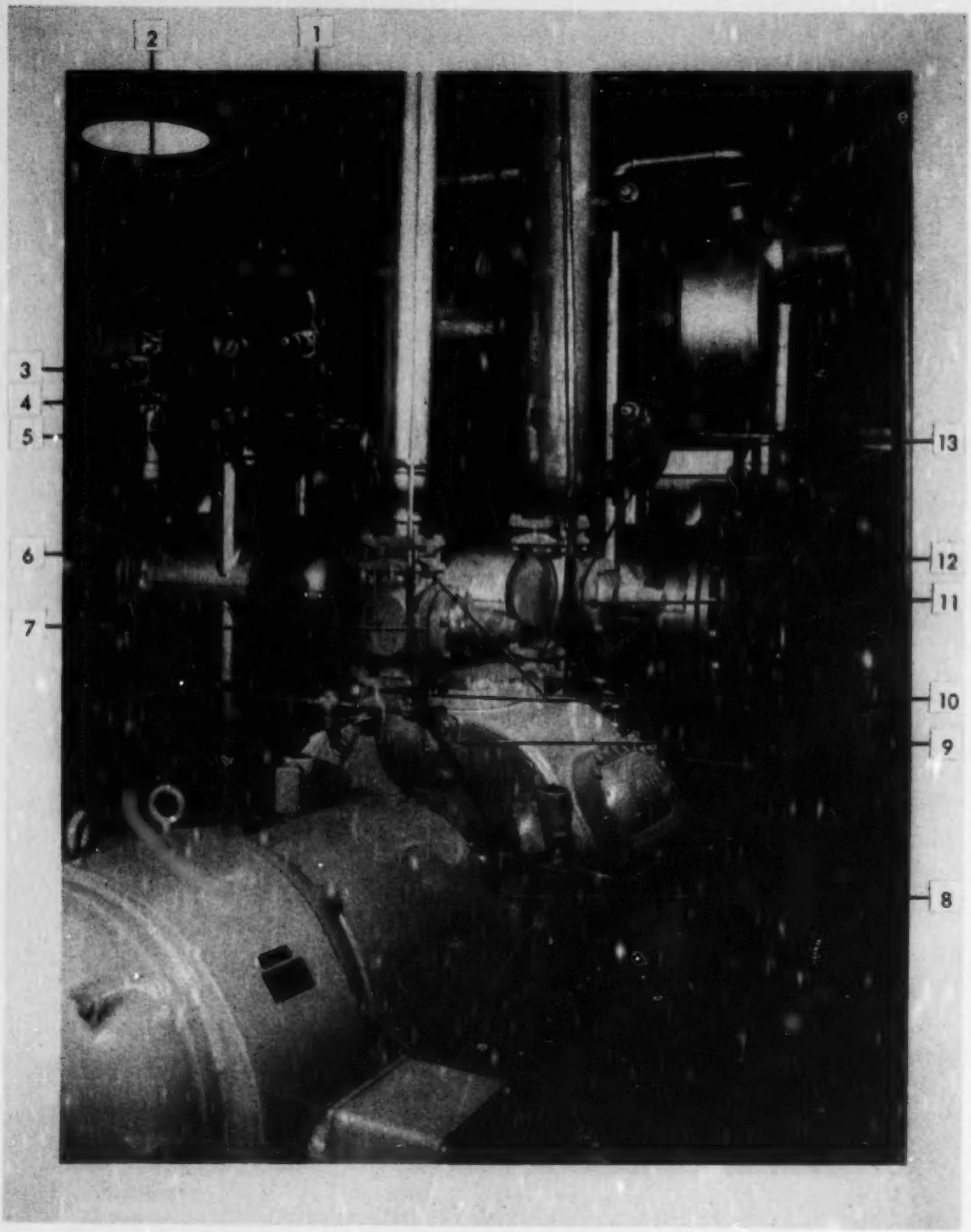

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Figure III-7. Reciprocating chiller system

5. Gasket on hand valve;

6. Gasket on condenser;

7. Valve cap gasket--high pressure side of compressor;

8. Compressor shaft seal (hidden);

9. Flange on high pressure side discharge line of compressor;

10. Flange on high pressure side discharge line of compressor;

11. Valve cap gasket--low pressure side of compressor;

12. Gasket on condenser; and

13. Flange on low pressure side discharge line of compressor.

The compressor shaft seal (Arrow 8) is hidden from view in this photograph by the rounded metal shield over the shaft from the electric motor (lower left hand corner with two metal rings on top) to the compressor. Immediately below Arrow 8 is a bolted plate to provide access to the lower portion of the compressor for inspection and repair of connecting rods, crankshaft, and other components. The gasket on this plate is a potential source of refrigerant leakage as is the gasket on the bolted compressor head immediately below Arrow 9. This particular compressor has six cylinders so that other compressor heads are located atop the machine between the two discharge lines and on the hidden side of the machine.

Pressure relief valves[46/] - The function of pressure relief valves is to release refrigerant in the event of excessive pressure increase because of some emergency, such as fire or equipment malfunction, so that the entire system will not explode. These valves are required by building codes for pressure vessels rated at 15 lb or more. The code also requires that these valves be vented to the atmosphere.

There are basically two types of pressure relief valves: mechanical and rupture. Rupture discs are either of the carbon type or the lead type. Mechanical pressure relief valves are used on high pressure (R-12) systems, whereas the rupture disc valves are employed on low pressure (R-11, R-113) centrifugal machines. The basic problem with mechanical pressure relief valves is that once the valve relieves excess pressure, it has a tendency to leak until replaced; reseating is also a problem. Obviously, the valves are not designed in this manner but, in practice, failure to reseat is a common fault. The placement of the mechanical relief values in the system can also lead to refrigerant loss. In reciprocating chillers, these valves are commonly placed on the condenser but the system is designed to operate fairly close to the burst pressure of the condenser. Thus leakages from this arrangement are rather commonplace.

Carbon or lead rupture discs appear to have a two-fold problem: initial leakage around or through the disc and, with age, premature rupture at pressures lower than the rated pressure. When a rupture disc bursts, the entire charge of refrigerant can be lost to the atmosphere. It is generally conceded that sooner or later, nearly all of the discs will leak within their normal lifetime of about 2 years. Another problem can arise as a result of air leaks into low pressure systems. When the unit is shut down, the purge is not operating. Air can leak into the system. Upon starting the unit, the purge system cannot instantaneously remove the air so that the refrigerant pressure plus the air can exceed the pressure rating (14.5 to 15.5 lb) of the disc and result in its rupture.

In previous units, some rupture discs were backed up with a mechanical pressure relief valve, but this arrangement can lead to a dangerous situation. If air leaks between the two valves, a small pressure will build. Since the rupture disc operates on a pressure differential basis, an abnormally high pressure in the system could result before the pressure differential would rupture the disc. If the mechanical valve is placed in front (on the machine side) of the rupture disc, this problem probably would be eliminated.

A recent example of the magnitude of refrigerant loss due to malfunctions of pressure relief valves can be cited. Kansas City International Airport uses centrifugal chiller systems with a unit charge of about 15,000 lb of refrigerant (R-12). A pressure relief valve on a unit there malfunctioned at a pressure below the rated pressure and released over 10,000 lb of the refrigerant into the atmosphere.

Purge systems - Purge systems are installed only on low pressure (R-11) centrifugal units. Since these units operate at low pressure, it is necessary to remove air, due to leaks, from the refrigerant. These systems are probably the major source of continual refrigerant emission from low-pressure units to the atmosphere. The primary difficulty with the present purge systems is that they are not very efficient in the separation of the air from the refrigerant, resulting in a loss of the refrigerant along with the air. All purge systems have these problems.[46/] It has been stated that from approximately 3 to 5 lb of refrigerant are lost for each pound of air removed from the unit.[18,48/] Not all purge units operate in the same manner but they are all based on the principle of pressure differential. For some units, a float-valve arrangement is used to periodically release the air to the atmosphere.[48] Other systems use a compressor arrangement whereby the air is continually released to the atmosphere.[45] With the float-valve arrangement, one of the operational problems is due to the floats on the valves sticking and allowing excess refrigerant to pass with the air. The problem with the floats is caused by an accumulation of particulates, oils, and other contaminants removed from the refrigerant.[48] With all systems, if the purge pump has carbon piston rings, considerable backside leakage will occur.[46]

Compressor shaft seals[46] - Shaft seals are present on reciprocating chillers and some centrifugal units (open-drive systems). Seal leakage is one of the more common leakage problems but represents a gradual loss of refrigerant rather than a large single incident loss. Open-drive centrifugal units are not as prone to leakage as the reciprocating units because they have an oil reservoir at the seal to keep it lubricated during periods of nonuse. This oil reservoir is not present on reciprocating units.

Shaft seals are manufactured from either carbon or ceramic. Carbon seals are generally used on low pressure units but have been used to some extent on high pressure systems. Open-drive centrifugal units primarily use carbon seals. Ceramic seals are used basically only on high pressure reciprocating compressors.

The principal problems with shaft seals arise during periods of nonuse, i.e., during the winter months. During this period of time, the oil necessary to lubricate the seal drains away from the shaft and the seal is allowed to dry. As a result, the seals will have a tendency to stick or "freeze" on the shaft so that when the machine is started, the shaft will tear away from the seal and create small imperfections in the seal surface through which the refrigerant can leak. Generally, if the seal does not have any major damage, it will reseat and stop leaking after the unit has been running for about 2 to 3 hr. Another source of seal leakage occurs if small particles of dirt, metal, etc., work their way between the shaft and the seal. When this happens, the surface of the seal becomes "scored" and continual leakage of the refrigerant will occur. A third cause of seal leakage and compressor failure is due to "slugging" of the compressor by relatively large quantities of liquid refrigerant (or oil) entering the cylinders during machine start-up. Overcharging with refrigerant can also cause "slugging" to occur. If "slugging" occurs, it leads to extremely high pressures being developed within the compressor and will cause seal leakage, blown head gaskets, or valve and cylinder damage.[49]

The actual amount of leakage from the seal is relatively small for each machine. Many of the units using seals are 100 ton or lower capacity units, with a refrigerant capacity of less than 500 lb. However, the vast majority of the chiller systems are in these lower tonnage units so that, while the quantity leaked from each unit is small, the cumulative effect is quite significant.

Gaskets and O-rings[46/] - Gaskets are a very common source of leakage in chiller systems. The reasons for leakage appear to be two-fold: the materials of gasket construction, and the manner in which the flanges are connected. Flat gaskets and O-rings for bolted joints can be constructed from rubber, buna-N, neoprene, asbestos compositions, or other materials. Rubber and buna-N will readily break down in the refrigerant-oil atmosphere within the system and show severe leakage. However, these materials are still used in some equipment. Flat gaskets are generally produced from an asbestos-type material.[18/] The most common material for O-rings is neoprene, which is favored because it is sufficiently soft that the joint faces do not have to be perfectly flat or smooth. Because of its softness, the neoprene will flow into the imperfect faces and form a good seal. However with time, neoprene will deteriorate, harden or flatten. Due to the continual heating and cooling of the machine, the neoprene will crack and develop leaks. The normal lifetime for flat gaskets and O-rings is approximately 3 years before severe leaks develop. This lifetime is also dependent on the size of the unit and how often it is operated.

Large O-ring gasketed flange joints are normally either bolted or clamped with a "V" band, which resembles a barrel hoop used to clamp lids on barrels. The bolted flanges generally provide an acceptable joint with respect to leakage. However, the "V" band is considered a poor arrangement and will consistently show leakage.[46/] Small vibrations in the system are one of the causes of "V" band leakage. Even with no unit vibration, after a period of time the "V" band will stretch and leaks will develop. Dresser couplings have been used in the past for joints but have largely been replaced due to their tendency to leak refrigerant. Some older machines may still be equipped with these couplings.

Miscellaneous minor sources[46/] - Some relatively minor sources of refrigerant leakage which are common to all chiller systems will be briefly noted or discussed under this heading.

Vibration in chiller units has been a problem area in the past but the manufacturers have successfully dealt with this problem. Line cracking and breakages do occur occasionally but not to the degree as in past years.

Compressor motor terminals are a common source of small leakages of refrigerants. Solder joints and the use of flare fittings are frequent sources of refrigerant leakage. These methods are common leak points on all types of refrigeration and air conditioning equipment.

Service and Repair Operations - The previous subsection discussed sources of leakage due to equipment failure. In this subsection, refrigerant emissions directly related to the service and repair operations on chiller systems will be discussed.

Repair operations - Any repair work conducted within the system will normally require the removal of the refrigerant charge. For certain types of failures, the refrigerant may become contaminated while in other failures, no contamination will occur. Two common problems which result in contaminated refrigerant are the bursting of a frozen water tube, leading to water contamination[50] and an electric motor "burnout" in hermetic systems to produce a hydrochloric and hydrofluoric acid contamination of the refrigerant. Safety controls are present to prevent the freezing of water tubes. These valves should be checked and recalibrated annually, but this is apparently very seldom done.[46] Other repairs, such as an overhaul of the compressor or the welding of a cracked refrigerant line, would require the removal of noncontaminated refrigerant prior to the repair operations.

Most manufacturers of high pressure (R-12) units of 100 tons or more build a transfer pump system and receivers into the unit so that most of the refrigerant can be transferred while repairs are being made. Lower capacity units do not have a built-in transfer system so that a transfer pump must be supplied by the service personnel. In certain instances in small units, it may be possible by the use of valves to isolate quantities of the refrigerant in sections of the unit not undergoing repair. However, based on discussions with manufacturers[45,48] and service personnel[46] and despite some claims to the contrary, most of the contaminated refrigerant (either water or acid) appears to be either purged to the atmosphere or dumped into a sewer drain. This is true regardless of the size of the unit. For noncontaminated refrigerant in a unit equipped with a transfer system, that quantity which can be conveniently and rapidly transferred will be saved and the remainder discarded to the environment. Anonymous sources in the air conditioning repair sector state that for small capacity units with no transfer system, the vast majority of even noncontaminated refrigerant is discarded, either to the atmosphere or to a sewer drain. Refrigerant disposal practices may also depend on other considerations, such as who will pay for the replacement refrigerant.

The rationale for the lack of recovery of used refrigerant is primarily one of economics. Because of the low wholesale cost of the common refrigerants, service personnel will recover only that quantity which can be isolated rapidly and conveniently. Economically, it is not feasible to spend time recovering a cheap component. Another quoted consideration concerns the containers to hold the refrigerant.[46] Most refrigerant is shipped in disposable drums which cannot, by law, be refilled. Each service unit would have to purchase new, refillable drums to hold the used refrigerant during repair operations. Cross-contamination of refrigerants could be possible unless the drums were cleaned after each usage or separate drums used for each type of refrigerant.

Service operations[46] - Service operations generally are not responsible for the creation of refrigerant emissions, but are partially responsible for the perpetuation of existing emissions, primarily in the area of small leakages. It is not rare for a unit, low on refrigerant, to be refilled but not checked for leaks to determine how the refrigerant is being lost. It has been stated that perhaps too many repair organizations are becoming "refrigerant sellers" rather than attempting to detect and repair leakages, particularly the smaller ones.[46] Certainly a portion of this failure to repair leakages can be attributed to the customer, who would prefer to pay for the added refrigerant rather than shut down the unit to repair the source of leakage. For a single unit, the quantity lost may be small but the total number of such units is large.

Potential Methods of Emission Control - In this discussion, an attempt will be made to present some possible changes in both equipment and procedures which would lead to a reduction in refrigerant emissions. This discussion will consider both the equipment failures leading directly to refrigerant emission and service and repair operations.

General considerations - Essentially all chiller manufacturers recommend an annual oil change, filter change, equipment test, and leak test.[45,48] The term, equipment test, is used to designate items such as floats, valves, switches, etc., that can be checked and tested to assure proper operation. Certain items, such as rupture disc pressure relief valves, obviously cannot be tested without rendering that piece of equipment inoperative. Service companies also recommend an annual leak test on all chiller systems.[46] While these procedures are recommended, they are seldom actually performed or often performed in a very cursory manner. The performance of leak testing and the repair of faulty equipment could diminish refrigerant emissions to a considerable but unknown extent.

An indirect method which is concerned with the overall system might be the addition of a leak detection system with an audio and/or visual alarm device. While an alarm system of this nature would not prevent leakage, it would alert the maintenance personnel and/or service personnel that a leakage problem exists. An internal system that is currently employed with food and beverage refrigeration systems (p. III-55) may be adaptable to chiller systems.

For smaller leakages, in high pressure units, due to seals, gaskets, etc., multiple external gaseous refrigerant detectors could be installed at common leakage points. These detector systems, based on thermal conductivity or infrared detection methods, could be incorporated into a visual and/or audio alarm system. The cost of the detector systems range from less than $100 to approximately $2,000,[51] depending upon the degree of sophistication desired.

E. I. du Pont de Nemours has developed a system of refrigerant (R-12 or R-22) plus a red colorant (Dytel®) that would appear to be very effective in pinpointing many leakages from high pressure chiller units.[51] For sources such as flat gaskets, O-rings, and valves, a visual inspection would determine the presence of leaks and provide some indication of the severity of the leak.

Equipment failures - Manufacturers and service companies agree that, in general, preventative methods for these types of leakages encompass new equipment, better applications of existing equipment, and better operating practices. In the following discussion, methods for emission control will be delineated for each of the common sources of leakage. For modifications of existing designs or complete redesigns on new equipment, the cost of these modifications will be borne by the customer in terms of increased purchase prices.

Shaft seals[46] - The new, smaller tonnage chiller units are hermetically sealed systems which, of course, do not require the use of shaft seals. Of the new reciprocating chiller units that do require seals, the majority of these units use R-22; for those units employing R-12, the problems with seal lubrication appear to be considerably less than those found with the older machines. Therefore, the basic consideration is for the replacement of seals in existing units rather than new units.

The design of compressor seals is a complex field and, if satisfactory seal performance and reliability are to be attained, proper mechanical seal selection is critical. The two most common seal arrangements are single inside-mounted seals and double seals; single seals are used in chiller systems. Properly lubricated double seals provide good seal reliability and maximum protection against refrigerant leakage to the atmosphere or the entry of air and moisture into the compressor.[49] However, for current chiller systems, a complete redesign of the compressor seal housing and, possibly, a lengthening of the compressor crankshaft would be required to accomodate a double seal arrangement.[46]

The most feasible solution to the problem of seal leakage does not appear to be a new seal, either in design or material, but rather better operating procedures. If units employing a shaft seal were to be operated for a brief period of time each month during periods of nonuse, as recommended by manufacturers and service companies, this procedure would alleviate the seal seizure problem and considerably reduce leakage during machine start-up. During the winter months, some chiller owners pump the refrigerant into receivers and shut the valves so that the refrigerant is not in the system. This procedure will eliminate leakage of refrigerant through gaskets, joints, etc., but it also will prevent the system from being started periodically to keep the seals lubricated.46/

Leakage resulting from a "scoring" of the surface of the seal by dirt, metal particles, etc., can be detected by a leak test and the seal replaced.

Over pressurization of the seal by "slugging" may be reduced or eliminated by (1) circulating the refrigerant (or oil) into the motor prior to entering the compressor cylinder, (2) placing a suction accumulator (ballast tank) in the refrigerant line, or (3) combine 1 and 2. New semihermetic compressors are designed to circulate the refrigerant into the motor. A suction accumulator can be installed for approximately $100.52/

In many instances, there is no valid reason why hermetic compressors could not be used in new systems with the complete elimination of shaft seals.46/

Purge systems - For low pressure centrifugal units, this system probably accounts for more loss of refrigerant on an annual basis than any other single source. Since the sole function of the purge system is to remove air from low pressure chiller units, the elimination of sources of air leakage into the system would result in less air intake and, hence, a reduction in the use of the purge system. In actuality, low pressure systems (R-11 and R-113) could be replaced with high pressure (R-12) systems, if manufacturers were given sufficient lead time to produce small R-12 compressors. One company (Westinghouse) already produces small R-12 centrifugal compressors. A high pressure system would completely eliminate the need for purge systems and simplify the leak checking procedure to a considerable extent. The R-12 systems can use a hermetic compressor system, which could result in a tighter system and considerably reduce other leakages. The additional cost of such a system would result from redesign and retooling. These costs would, of course, be passed on to the consumer.18/

The same purge system is normally used for all sizes (tonnages) of chiller units.[48] For smaller tonnage units, the purge system can accommodate larger air leakages and the chiller will remain in operation; however, the larger air leaks also means that greater quantities of refrigerant are being lost to the atmosphere. If purge systems were to be scaled to the tonnage of the unit, a decrease in the quantity of air that could be accommodated in lower tonnage units would result. For a 250-ton low-pressure centrifugal chiller, the present cost is about $31,000 to $32,000. The factory cost of the complete purge system is approximately $500 to $1,000 with the bulk of the cost in the compressor and copper tubing.[48] This same purge system is also installed on small units, e.g., 75 ton units. While the exact material cost reduction in scaling the purge system to the unit size is unknown and may not be large, some cost reduction should be possible.

For those purge systems employing a compressor with carbon rings, the use of a piston type compressor with standard rings and seals would considerably reduce the backside leakage.[46]

A more efficient purge system could easily be designed; it is simply a matter of economics. By combining higher pressures with lower purge condensing temperatures, the ratio of the quantity of refrigerant to the quantity of air emitted from the purge system can be reduced to almost any desired level. However, as the pressures increase and the temperatures decrease, the cost of the purge system increases. As an example, if an extra compressor and a low temperature (R-22) condensing unit were added, a refrigerant to air ratio in the expelled gas of 1:1, as opposed to the current 3 to 5:1, could easily be attained. The cost of such a system would probably be approximately three times the current cost of a purge system.[18]

For existing purge systems, an auxiliary low temperature condensing unit could be installed in the vent system to remove a portion of the refrigerant from the air prior to release into the atmosphere. Based on current refrigerant levels in the expelled air, a significant recovery of refrigerant may be obtained, depending upon the temperature of the auxiliary condensing unit. It is estimated that a condensing unit would cost less than $500, not including installation.[44]

Flanges and gaskets - As discussed previously, flanges and gaskets are common sources of small leakages of refrigerant primarily because of the temperature variations in the system. The flanged joints on service and control valves have been of about the same design for approximately 40 years. Most of the valves are adapted ammonia valves with seal caps instead of hand knobs. Seal caps simply retain the leakage instead of allowing it to discharge directly into the atmosphere; however, when the seal cap is removed to turn the valve, the gas escapes to the atmosphere. The flanges used on these valves either need to be considerably improved or completely eliminated.53/ One possibility lies with imported European flangeless valves. If done properly, e.g., metal to metal welded joints with an interior O-ring, a very tight joint can be obtained. The cost of flangeless valves are comparable to valves made in the U.S.18/

Bolted flange O-ring joints generally will provide a tight seal and show little tendency towards leakage, if properly installed.46/ Polymeric fluorocarbons, e.g., Teflon®, could be used for flat gaskets and O-rings. This material should not show the tendency to crack or split that presently occurs with neoprene or asbestos type materials. However, since Teflon® is not as soft as the other materials, the finished faces of the flanges must be more smooth and straight than the current faces.

Instead of a gasketed joint, a tighter seal would result by using a metal to metal joint with provision for an O-ring. The primary cost for these joints would occur in the machining of the flange faces. For flanged joints on the compressor, some redesign may be necessary.18/

Dresser-type gaskets have generally been replaced in most systems. In certain instances, existing gaskets of this type may be able to be replaced by welded joints.46/

As stated previously, "V" band clamp systems are prone to leakage. Due to the method of construction, it would be extremely difficult to alter existing "V" band arrangements.46/ While a different connection would seem advisable, it appears that little can be done to existing systems to install a new arrangement.

Pressure relief valves - According to one source, the carbon disc pressure relief valves, used solely on low pressure centrifugal units, should be replaced on an annual basis.18/ A service company source states that if the valve is not leaking, carbon rupture disc valve should remain until leakage occurs.46/ Due to the nature by which the rupture disc operates, preinstallation testing or periodic testing cannot be performed. One solution may be to install a refrigerant leak detector with an audio and/or visual alarm in the vent pipe on the atmosphere side of the disk. In this manner, maintenance personnel will be alerted if the disc is leaking refrigerant and the disc can be replaced. Inexpensive leak detectors can be purchased for less than $100.

Mechanical pressure relief devices, used on high pressure chiller units and some low pressure units, can be designed to reseat properly and reduce leakage by applying greater spring pressure on the valve.18/

According to this source, reliable mechanical pressure relief devices are available if time is taken to look for them. It would seem appropriate to pressure test mechanical relief devices immediately prior to their installation to determine if the valve will reseat properly and not leak. Valves that do not meet specifications could be returned to the manufacturer.

One possibility for both rupture disc and mechanical devices would be the installation of an appropriately sized pressure-rated vessel in the vent system to collect refrigerant lost due to leakage or release of the relief device. This pressure vessel could be vented to the atmosphere with a pressure relief device in its vent pipe. A pressure gauge should be added to the tank to indicate the internal pressure. This tank could be of an appropriate size so that, under ambient temperatures, it could hold the entire refrigerant charge without venting through its pressure relief valve but in an emergency, e.g., a fire, the charge will be vented to the atmosphere to provide firefighter safety. This auxiliary system would: (1) prevent direct leakage to the atmosphere; (2) provide a means for refrigerant recovery in the event of a premature discharge from the relief valve or a mechanical failure in the chiller system (e.g., loss of cooling water, etc.); and (3) still provide safety in case of an emergency such as fire. However, it is possible that a system such as this may be in conflict with local building codes to allow its installation. The cost of an appropriately size pressure-rated vessel would be dependent upon the refrigerant charge of each chiller unit.

Miscellaneous sources - For the piping system around compressors, brazed joints, instead of soldered joints, could be used to provide a tight system.[53/] Compressor motor terminals are a source of small leakage. Hermetic type terminals that are threaded could be used instead of the gasketed type. However, the advantage may be very small because the terminals are a source of small leakage.[46/]

Refrigerant recovery - Refrigerant recovery systems applicable to chiller systems are available from various equipment manufacturers[23/] and at least one refrigerant producer.[24/] These systems have been discussed earlier in this section. Since large-scale chiller systems (> 100 tons) normally are equipped with built-in pumps and receivers, the primary systems requiring external transfer and storage equipment are those units of less than 100 tons or contain less than 500 lb of refrigerant.

For the other types of refrigeration and air conditioning discussed in this section, the basic consideration is economics because of the relatively small quantity of refrigerant per unit and the low cost of the refrigerant. Economics certainly are also a factor with respect to chiller systems. For units up to 20 tons, the refrigerant capacity is less than 50 lb so that unless the transfer, storage, and refilling can be conducted rapidly, the collection of refrigerant, based solely on economic factors, is probably not feasible. If the refrigerant is contaminated, either "wet" or "acid", a purification process must also be included.

With larger chiller systems (e.g., 60-ton units containing 150 to 200 lb of refrigerant), the decision whether to collect the refrigerant or not may be a matter of convenience as well as pure economics. For noncontaminated refrigerant, the release of this material to the atmosphere appears to be almost solely a matter of convenience, although there certainly is an economic factor to be considered. In the case of contaminated refrigerant, the purification process must be considered so that, in terms of pure economics, the ultimate "cost" of recycling would be dependent upon the quantity of refrigerant and the degree of contamination. E. I. du Pont de Nemours, for example, will purchase certain contaminated refrigerants for recycling. Systems are also available for the repair organizations to do their own recycling. In the final analysis, it appears that the decision to recovery refrigerants is a combination of economics and incentive.

Possible options - The following brief discussion of some possible options is presented here because it seems to be more appropriate to chiller systems, because of their large capacities, than to the other types of refrigeration and air conditioning. The enactment of regulations, either with or without capacity exemptions, is an obvious possibility. Within the scope of regulations, the potential effectiveness of the enforcement must also be considered both in terms of possible fines for noncompliance and the degree or scope of the enforcement activities. Enforcement possibilities could exist at the regional EPA level.

Aside from the regulatory possibilities, the concept of economic incentives for recovery and reuse could also be considered. Possible incentives could be in the form of direct grants for recycling services, subsidies for recycling, potential tax write-offs, and governmental procurement (ETIP). In the area of potential tax write-offs, consideration may be given not only for the reuse of refrigerant, but also to the possible conversion of existing chiller systems, which often necessitates equipment changes, to a "safer" chlorofluorocarbon refrigerant (e.g., R-22).

A third possible set of options may be a mixed strategy in which it may be possible to combine a regulation with various incentives timed in such a manner as to counter the exemptions. This possibility might be conceived in a way so that as the recovery technology improves and it becomes more economically feasible to recovery refrigerant, the capacities of systems which would be exempt would likewise decrease.

It should be stressed that the above brief discussion represents a few possible options that might be considered _if_ some form of action were to be considered regarding deliberate emission of specific chlorofluorocarbons into the atmosphere. The option stated above should not, in any way, be construed as conclusions or recommendations by MRI with regard to this problem. Detailed studies of the legal, economic, political, and societal ramifications of this subject area are beyond the scope of this report.

COMMERCIAL FOOD AND BEVERAGE REFRIGERATION

In contrast to home refrigeration, much less marketing information is available for the commercial food and beverage refrigeration sector. Direct contact with associations such as National Commercial Refrigeration Sales Association and Commercial Refrigerator Manufacturers Association failed to produce industry-wide marketing data, e.g., annual sales, number and kinds of units sold, replacement sales, market saturation, growth trends, etc. Such information is deemed confidential by association members.*

The commercial refrigeration equipment field is dominated by Hussmann Refrigerator Company, St. Louis, Missouri, a division of Pet Incorporated, which has captured approximately 35% of the market.54/ By contrast, several companies, including C. Schmidt Company of Cincinnati, Ohio, and Golden Cabinet Company of Carlstadt, New Jersey, have an estimated combined 5% market share. The remaining 60% of the market is divided among the four companies:

Hill Refrigeration Company, Division of Emhard Corporation, Trenton, New Jersey;

Warren-Sherer Company, Division of Kysor Industries Corporation, Marshall, Michigan;

Tyler Refrigeration Corporation, Niles, Michigan; and

Friedrich Air Conditioning Refrigeration Company, Division of Weil-McLain, Inc., San Antonio, Texas.

No individual sales data are available at this time.

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* The marketing and technical information reported in this portion of Section III was supplemented by data from the Hussmann Refrigerator Company.

Most types of commercial refrigerators are shipped from the factory with evaporator coils but without compressors, condensing units, or refrigeration equipment. Remote condensing units or refrigeration systems are installed on location with appropriate refrigeration components supplied by the manufacturer or a contractor.

Manufacturers of commercial refrigeration equipment do not generally manufacture the entire refrigeration condensing unit, but rather rely heavily on components supplied by other manufacturers. Thus, the manufacturer purchases the motor-compressor, condensers, receivers, tubing, valves and other fittings, electrical components, and numerous small hardware based on the design and specification. The manufacturer does design and manufacture the steel control panel enclosure for the condensing unit.

Much emphasis is placed on engineering design to reduce overall energy consumption by balancing store cooling, heating, and dehumidification requirements, along with refrigerator cooling and defrosting, in retail stores. The manufacturer designs and assembles the food and beverage display cases, coolers and freezers which generally are connected by piping to refrigeration units in a separate location in the store. The energy requirements of the equipment are affected by temperature and humidity in the store. For this reason, proper design of the air conditioning and heating system to provide optimum conditions in the store is important. Some refrigerator manufacturers provide this equipment.

Estimated Refrigerant in Use and Annual Losses

According to one source 80 ± 5% of all commercial refrigerant presently in use for food and beverage storage and display cases is R-12.[54] New and remodeled installations are using R-502 for low temperature applications, e.g., frozen food and ice cream storage and display, and R-22, R-12, and R-502 (small quantities) for medium temperature application, e.g., meat, produce, dairy, and delicatessen. For example, R-502 has been used exclusively in low temperature application for at least the last 15 years, with R-12 only being used for refrigerators displaying those products above freezing. In the near term time interval, e.g., to 1985 to 1990, emissions from commercial refrigeration within the present scope of inquiry will primarily consist of R-12; but by the year 2000, if present trends prevail, emissions will be essentially R-502 and R-22.

The total amount of R-12 refrigerant in the commercial food and beverage storage and display sector in 1973 has been estimated.[1] From the published data, the total refrigerant, as R-12, in service for this sector in 1973 is estimated to be near 150 million pounds. The annual R-12 emissions are estimated to be near 28.2 million pounds.

By contrast, one industrial source estimates the total amount of R-12 refrigerant in all classes of grocery stores is near 73 million pounds.[54] Table III-5 utilizes data from a grocery trade magazine.[55]

Table III-5. ESTIMATED QUANTITY OF R-12 IN GROCERY STORES (1975)

Store classification	Business volume ($)	Number of stores[55]	Average lb R-12 per store[54]	Total lb R-12
Super markets (including chain and independent operations)	1,000,000 +	31,710	1,200	38,052,000
Superettes	500,000 to 1,000,000	12,800	600	7,680,000
Small stores (including chain, small stores, and independent small stores)	< 500,000	122,300	200	24,460,000
Convenience stores	< 500,000	25,500	100	2,500,000
Total	-	191,810	-	72,692,000

If the estimate of 73 million pounds of R-12 currently is used is reasonably correct, the annual emissions of R-12 may be more nearly 14 million pounds, instead of 28 million pounds.

Sources of Chlorofluorocarbon Emissions

Present state-of-the-art commercial food and beverage refrigeration units consist of three basic approaches. The first being a bank of four semihermetically sealed motor-compressor units (5% of total installations) connected in parallel to a manifold of isolation and regulating valves which serve evaporators and condensers. The latter components serve either normal temperature coolers or display refrigerators for fresh foods (R-22) or low temperature frozen food lockers or display refrigerators (R-502).

Refrigerators are connected to the compressor banks by tubing on the jobsite. The parallel arrangement is an energy saving feature because one or more compressors can cycle on and off as the demand varies. This system generally does not employ the use of R-12. The discussion is presented to indicate the present state of the art in this area. It may be possible for R-12 to be used in this system, but its usage would very likely result in lower operating efficiencies and a possible increase in energy consumption.

The second approach involves two compressors mounted in parallel instead of four, but with other factors being essentially the same. These installations represent about 10% of the total installations.

The third and by far the largest installation practice is the installation of a single condensing unit connected in parallel to one or more refrigerators for identical utilization, for example, five or six refrigerators serving produce refrigeration and display. These installations represent about 85% of the total installations.54/

Extensive use is made of heavy walled copper tubing with brazed joints using silver solder. Special aluminum-copper transition solder joints are provided by the refrigerator manufacturer for joining aluminum evaporators to copper tubing when aluminum is used.

The compressors are generally fractional horsepower through 25 h.p. semihermetic units which are sealed units in the sense that the motor and compressor are sealed in a common housing in which the refrigerant circulates freely. There are one, two, or three bolted, gasketed cylinder heads for removal and replacement of valve plates in each bank of cylinders. These portions of the motor compressor are potential leakage points.

There are suction and liquid lines running to the refrigerators and also discharge and return lines to and from the condensers which in some instances are roof mounted. If the joints have been properly brazed, there is little chance for leakage. The suction lines in some stores are insulated to prevent condensation and building damage and does provide some protection to the tubing.

Vibration in the entire assembly of components is kept to a minimum by proper physical supports and engineering design. Vibration eliminators are mounted in the piping on some installations.

A multi-valved manifold panel permits each line to a food storage cooler, or display refrigerator to be regulated, isolated, or tested for leaks. Each line has an individual capped service port. These components are all potential leak points. There may be as many as 100 potential leakage points in the manifold system serving a large supermarket.

Sophisticated systems such as these have at least three methods for detection of refrigerant leakage or malfunction:

1. An automatic bell alarm which warns employees in the store of malfunction of the system and rising temperatures in freezers and coolers. This alarm/warning system is actuated by a floating lever arm mechanism in the liquid refrigerant receiver. When the float on the liquid refrigerant falls below a predetermined level in the receiver, the lever-arm attached to the float trips a relay switch sounding the bell alarm and automatically contacts the service organization and/or the grocery chain maintenance engineer at the central office.

2. Same as the above but the alarm only goes off in the store.

3. These automatic warning systems are backed up by routine checking by employees of the supermarket who are required to visually check thermometers located within each cooler, refrigerator, freezer, or display case.

The last backup technique to the automatic alarm systems is not dependable according to a maintenance engineer who is employed by a Kansas City-based grocery chain. Grocery clerks, meat cutters, and helpers simply cannot be depended upon to monitor the cases daily.

Figure III-8 presents a schematic diagram of the current state-of-the-art multiplexing arrangement for supermarkets. Several compressors are combined in parallel to serve various parallel arrangements of coolers, freezers, beverage cases, and other display refrigerators. The figure indicates a common condenser, usually roof-mounted. Other portions of the refrigeration system are self-explanatory or indicated in the figure.

A very few large supermarkets not of recent vintage have refrigeration systems, employing R-22, that are termed "compounded" in which the store has one or more medium temperature compressors and one or more low temperature compressors connected in series with the medium temperature compressors. The medium temperature compressor has a suction line not only from the low temperature compressor, but also from the medium temperature refrigerators. The suction line to the low temperature compressor comes from the low temperature refrigerators. Both types of compressors run constantly. However, they are designed for "compressor unloading," i.e., as the load requirements decrease for the refrigerators, one or more of the compressor cylinders become "unloaded" and do not pump refrigerant; the piston simply moves freely in the casting.

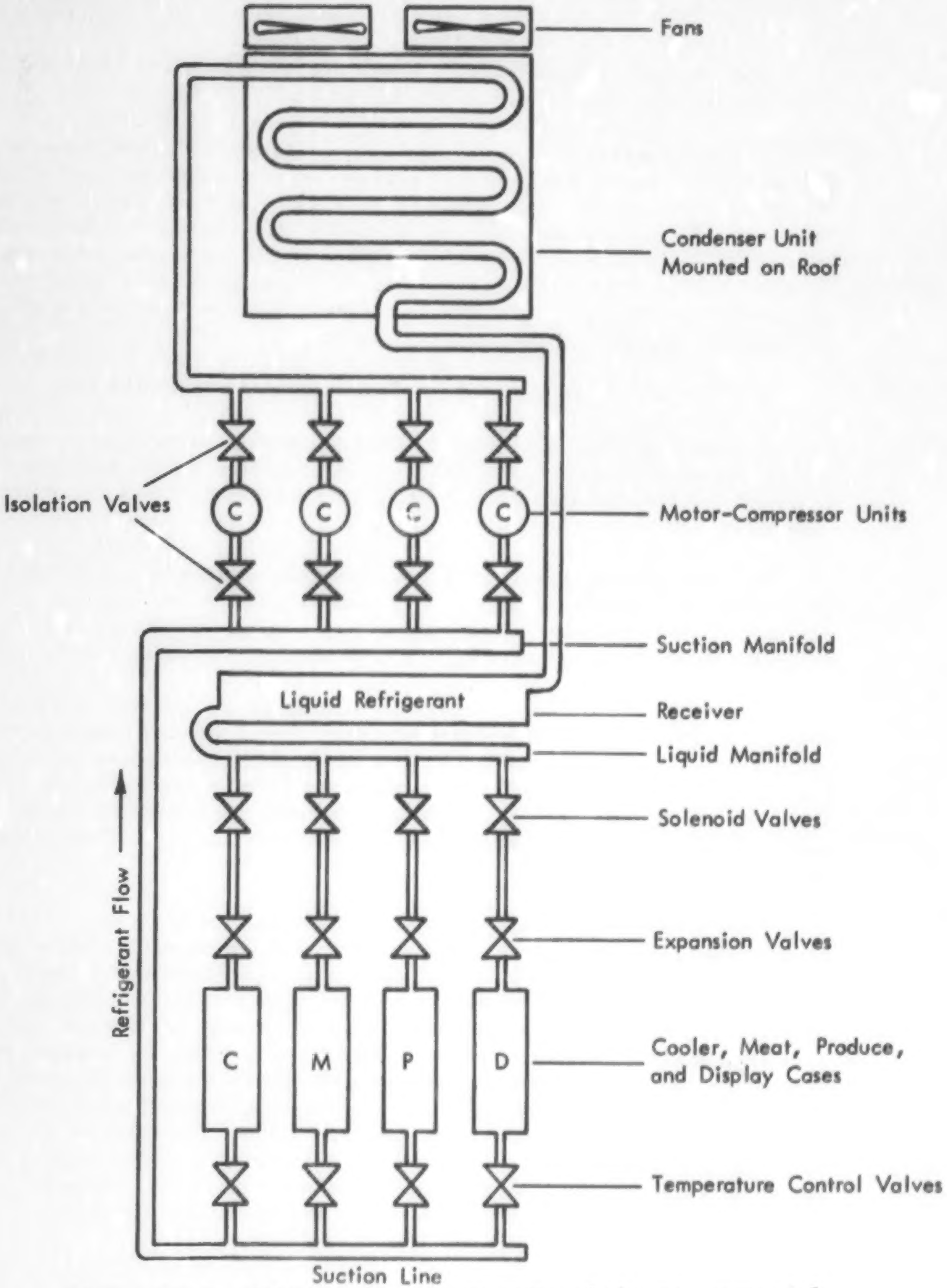
Fans
Condenser Unit Mounted on Roof
Isolation Valves
C
C
C
C
Motor-Compressor Units
Suction Manifold
Liquid Refrigerant
Receiver
Liquid Manifold
Solenoid Valves
Refrigerant Flow
Expansion Valves
C
M
P
D
Cooler, Meat, Produce, and Display Cases
Temperature Control Valves
Suction Line

Figure III-8. Schematic of current state-of-the-art commercial food and beverage refrigeration systems

Direct drive compressors are used which utilize a shaft seal. Leaks may be a minor problem if the system was originally properly installed, e.g., nearly vibration free, brazed joints, etc. However, the previous comments regarding potential refrigerant emission sources are equally valid for these systems.

Older and modern day R-12 refrigeration systems for supermarkets and small grocery and liquor (package) stores rely on a number of individual condensing units serving several similar display cases or coolers at the same temperature level. Even though only one condensing unit is attached to the food and beverage refrigerators, the compressor does cycle on and off based on the specific requirements of the refrigerators.

Figure III-9 presents a schematic of a very old R-12 type of conventional refrigeration assembly. In this particular arrangement a belted, open compressor is driven by an electric motor. The compressor serves three coolers or display cases hooked together in a parallel arrangement with the single compressor. This type of belt driven compressor is at least 20 to 25 years old.

Sources of refrigerant leaks in very old systems include the compressor crankshaft seals, the cylinder head gasket, various isolation and purge valves, any vibration sensitive joints and seals (typical older refrigeration systems were often poorly designed and installed with little thought to eliminate vibration), various isolation valves and purge ports, etc.

A visit to a local package store built 30 years ago revealed a complex arrangement that had grown over the years with little or no redesigning of the total refrigeration systems. Four 1.5 h.p., belted, open-compressors served five food and beverage display cases, a large walk-in cooler, and an ice cream display case. The compressors ran continually and the refrigeration system was obviously taxed to its limit. All four compressors exhibited excessive vibration, because of improper installation or inadequate motor mounts. A flexible metal hose was attached to one compressor which was vibrating much worse than the others. All metal piping exhibited some vibration from each of the other compressors. Often the vibration was noticeable for several feet from the compressors.

Uninsulated copper piping was used throughout the system. Joints and fittings were soldered (presumably silver solder was used) and several joints had been soldered many times as evidenced by large amounts

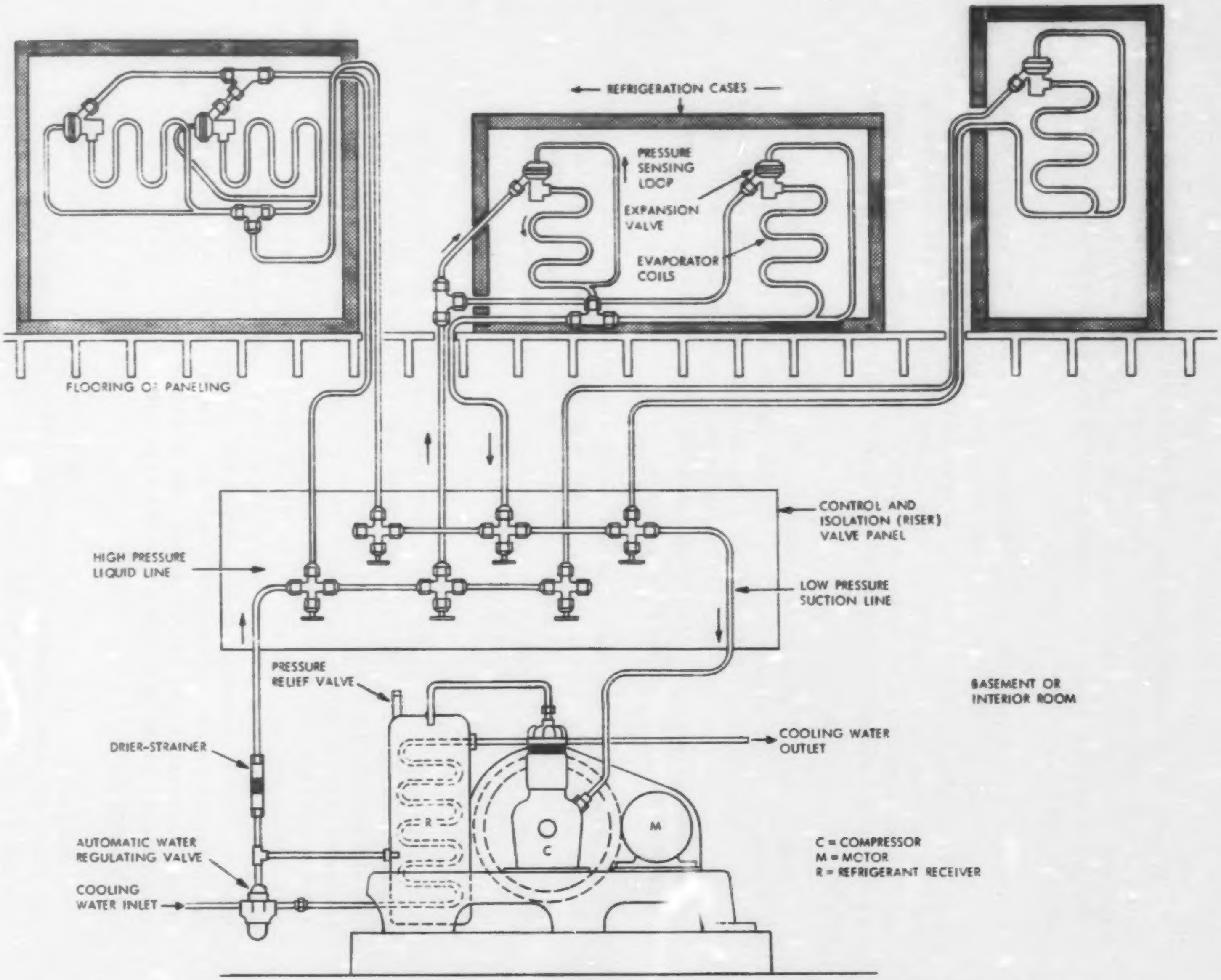
REFRIGERATION CASES
PRESSURE SENSING LOOP
EXPANSION VALVE
EVAPORATOR COILS
FLOORING OF PANELING
CONTROL AND ISOLATION (RISER) VALVE PANEL
HIGH PRESSURE LIQUID LINE
LOW PRESSURE SUCTION LINE
PRESSURE RELIEF VALVE
BASEMENT OR INTERIOR ROOM
COOLING WATER OUTLET
DRIER-STRAINER
AUTOMATIC WATER REGULATING VALVE
COOLING WATER INLET
R
C
M
C = COMPRESSOR
M = MOTOR
R = REFRIGERANT RECEIVER

Figure III-9. Typical old commercial food and beverage refrigeration system

of solder splashed on the piping which was heavily oxidized by excessive heat. Servicing of the units was accomplished through extensive use of capped valves. Many fittings and couplings were observed as potential leak points. The proprietor did not routinely check thermometer readings, but merely spot-checked unit performance on an irregular basis. There was no regular maintenance service call, but rather, the proprietor contacted a local maintenance company when a problem occurred.

These examples represent the extremes in current food and beverage storage and display refrigeration systems. On the one hand, systems of excellent engineering design and installation and under constant maintenance and inspection are found in the field. Conversely, many small add-on systems, improperly designed, installed and maintained also exist. Unfortunately, all systems can lose refrigerant through many similar potential points. The principal cause of leaks is a result of vibration in the following areas:

Brazed joints

Compression fittings and plates

Isolation and purge valves

Seals in belted, open compressors in older systems

Fitting fatigue

Elbow fracture

Capillary tube rupture

Particularly vulnerable are the service valves. Graphite packing often fails to hold refrigerant. In addition, poor and inadequate operating and maintenance procedures can contribute to refrigerant release to the atmosphere; e.g., unnecessary purging of refrigerant during servicing with no attempt to transfer and contain the original charge. Of course, leakage of refrigerant can occur in the condenser and evaporator units as well as through metal rupture, corrosion, improperly brazed joints, etc.

Service and Maintenance Practice

Large refrigeration systems in supermarkets can contain between 600 and 1,200 lb of refrigerant. An Arthur D. Little report on halocarbonds estimated an average of approximately 675 lb of refrigerant per store, about 80% of which is currently R-12.[1,54] The cost of refrigerant to the store owner is close to $1,300 when purchased in 50-lb drums, which is usually carried by a serviceman.

Failure in a supermarket refrigeration system does not necessarily require purging most of the system to isolate and repair a leakage point. A well engineered system will have many isolation valves. These features help in locating the leak and in minimizing losses during repair while permitting use of other parts of the total refrigeration system. Thus, when the refrigeration repairman checks the system, he invariably locates and isolates the problem area using a leak detector, thereby defining a very limited quantity of refrigerant for replacement. This may be much less than 100 lb if the problem is minor. The dollar loss of refrigerant may be of the order of $100, which is far less than the potential cost of spoiled or degraded food products.

Such is the current practice for small leaks or minor problems in commercial refrigeration systems. The service repairman locates and isolates the trouble point, e.g., a ruptured line, a leaky seal or fittings, etc. That section of the system is pumped down, thus causing the refrigerant to migrate to the receiver tank so that the rest of the system can be opened. The serviceman repairs or replaces the faulty component, evacuates the system several times to remove moisture and air, tests for leakage, charges the system with the proper amount of refrigerant, and tests for leakage again. If no leakage occurs, the appropriate valves are opened to allow the system to operate normally.

If a compressor fails or burns out due to "slugging" with liquid refrigerant or overloading, then the refrigerant in a large portion of the system may be contaminated with metal particles, decomposed motor winding insulation, oil, water, dirt, dust, etc. In this case, the serviceman may use filter-driers to remove contaminants from the refrigerant after replacing the compressor. Alternately, the serviceman may replace that portion of decomposed refrigerant with fresh refrigerant if, in his opinion, there is an undue risk to the system in using the original refrigerant even though it might have been passed through filter-driers. Both practices are found in the field.

In some instances purging of small amounts, e.g., 10 lb, of refrigerant to the atmosphere is common practice if the quantity of refrigerant in the system is small and the clean-up process is not economical.

Methodologies to Reduce and/or Eliminate Emissions

Hardware Improvement - Refrigerant loss occurs through leaks in components including accidental line rupture, fittings, valves, elbows, faulty compressors, faulty refrigerant control units, etc. The total refrigeration system is only as good as the components themselves and the manner in which they were engineered, installed, and serviced.

Generally speaking, older commercial refrigeration systems now in existence which have grown over time by the addition of more compressors and food and beverage refrigerators are the most troublesome to maintain properly and are the biggest source of refrigerant losses in the food store and beverage sector. Ideally, these systems should be retired and replaced with modern, efficient, properly engineered components including new display refrigerators to take advantage of current energy efficient systems. Remodeling or completely converting to a modern system would do much to reduce refrigerant losses since the older, belted, open-compressors would be retired.

The cost of modernization of refrigeration system would have to be borne by the owner-operator and would be substantial, perhaps amounting from $9,000 to $12,000 for a small grocery or package store and $250,000 for a large supermarket.54/ These costs would eventually be passed on to the consumer in the form of higher prices. The economic impact of such an updating has not been fully evaluated; however, a rough approximation of the costs accruing from this suggestion is given in Table III-6. This table presents a major commercial refrigeration company's detailed breakdown of estimated costs to replace existing large supermarket and small grocery store refrigeration systems.54/ The total amount for complete replacement of existing, older refrigeration systems, including display refrigerators, coolers, and storage cases, compressors, condensers, evaporators, labor, and materials ranges from $9,000 to $12,000 per store for small grocery stores (family owned; package stores; or small chain stores) to $222,000 to $279,000 per supermarket for large chain stores.54/

Several points must be made to fully understand the development behind Table III-6 for each type of grocery store operation. The small grocery stores do not have extensive, sophisticated refrigeration systems primarily because of individual preference, capital investment, operating cost, and/or cash flow limitations. These store owners would prefer to rely on modern hermetic, self-contained refrigerators similar to those found in the home. There would be no remote compressors and condensers, alarm systems, complicated parallel arrangements of units, etc., Consequently, the replacement cost of a new refrigeration system (neglecting trade-in value of older equipment and depreciation credits) would be primarily limited to the purchase of new self-contained display refrigerators plus installation charges, including labor, materials, and remodeling changes. The figure of $9,000 to $12,000 is based on 2,400 sq ft (a typical convenience style store operation) containing three to four refrigeration cases and no back room coolers or storage.

Table III-6. TOTAL ESTIMATED REPLACEMENT COST OF REFRIGERATION SYSTEM IN SUPERMARKETS AND SMALL GROCERY STORES

	Small grocery store ($)	Average supermarket ($)	Large supermarket ($)
Refrigerators and storage coolers	6,000-8,000[a]	40,000-60,000[b]	120,000-140,000[c]
Remote condensing units, including semihermetic compressors and remote condensers			
a. Single condensing units to coolers and refrigerators, or	-	12,000-17,000	35,000-40,000
b. Twins (two compressors in parallel), or	-	13,000-19,000	40,000-45,000
c. Quads (four compressors in parallel)	-	16,000-23,000	50,000-55,000
Walk-in coolers	-	6,000-10,000	20,000-25,000
Evaporators and fans	-	2,000-3,800	7,000-9,000
Installation, including labor, piping, and electrical services, controls, and refrigerant	3,000-4,000	13,000-22,000	40,000-50,000
Total per store	9,000-12,000	102,000-154,800	222,000-279,000

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[a] Small grocery store - 3 to 4 refrigerators per store at $2,000 each.
[b] Average supermarket - 20 to 30 refrigerators per store at $2,000 each.
[c] Large supermarket - 60 to 70 refrigerators per store at $2,000 each.

The large supermarket would probably completely strip the old refrigeration system including older display cases and coolers from the store. The calculations are based on such an event and are for a store containing 30,000 sq ft with 60 to 70 refrigerators and freezers at $2,000 each. The figure of $222,000 to $279,000 per store represents remodeling costs to the present state-of-the-art supermarket refrigeration systems, neglecting trade-in value and depreciation credits. On a nationwide basis there is a total of approximately 31,710 large supermarkets, 12,800 average supermarkets, and 147,000 smaller grocery stores;[55] however, not all of these stores would necessitate revision.

Short of a complete modernization of the entire system, where can the existing systems and component hardware be improved? The responsibility for hardware improvement lies with the component manufacturers, the total system manufacturers, the distributors, and the installation personnel and will require cooperation between these four economic units.

For older (over 20 years old) belted open-compressors the seal on the rotating crankshaft is a potential leakage point. Semihermetic motor-compressors which have been used for the last 20 years have eliminated this point source. The very old open-compressor has a single crankshaft seal because it was cheaper and easier to design and fabricate than a double-seal system. The latter system, when properly lubricated, offers greater reliability and maximum protection against refrigerant loss. It is not possible nor desirable to convert an older compressor from a single seal to a double seal system. If modernization of a refrigeration system is desired, then conversion to a semihermetic compressor is preferred. A discussion of improvements in seals, designs, and materials for large industrial components is contained elsewhere in the body of the report.

Another cause of compressor failure is due to "slugging" of the compressor by relatively large quantities of liquid refrigerant (or oil) entering the cylinder during start-up or refrigerant over-charging. This leads to extremely high pressures being developed within the compressor and causes seal leakage, blown head gaskets, valve and/or internal damage. Slugging may be reduced or eliminated by (1) designing the compressor so that refrigerant and oil circulates into the motor portion prior to entering the compressor cylinder in a semihermetic system and/or (2) placing a properly sized suction accumulator in the refrigerant suction line in series with the motor compressor unit. Older systems can be modified by adding a suction accumulator in the refrigeration suction line between the evaporators in the display cases and the motor-compressor. The cost of a suction accumulator is from $100 to $125 depending on the capacity required. Suction accumulators are readily available for brazing or welding into present commercial systems from several companies.[52]

New Operating and/or Maintenance Practices or Procedures - In practice the maintenance/service repairman must transfer a portion of the refrigerant from the large cylinders or drums to smaller service cylinders without loss of refrigerant. Careless transfer of the refrigerant from the large to the small service cylinders in the field can waste much refrigerant. A charging board or station consisting of a glass cylinder or measuring tube to estimate the amount of refrigerant in pounds, an evacuating pump, and various valves provides an accurate means of transfering refrigerant without loss. Charging boards are available in several sizes depending on the use, e.g., a highly portable unit for small to medium size systems in the field (as may be found in supermarkets) range from $3,000 to $3,800 and are capable of handling up to 145 lb of refrigerant. Larger industrial charging boards for use on production lines (for serving 25 to 100 cooling units per day) range from $6,300 to $12,700.23/

In many cases, e.g., small commercial systems in supermarkets, disposable refrigerant cylinders (cans) are used.56/ These pressurized service cans may contain 1 to 10 lb refrigerant and are operated by a special piercing valve assembly which is clamped to the top of the can. The cans are convenient for charging known quantities of refrigerant into commercial systems without loss when used in conjunction with a charging board.

Present technology for dehydrating refrigeration systems by high vacuum technique and recharging with a precisely measured quantity of refrigerant has been developed to a high degree over the past 35 years. Field service repairmen can readily take advantage of this technology in reducing refrigerant handling losses to a minimum.

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SECTION IV

FOAM BLOWING AGENTS

CHLOROFLUOROCARBON CONSUMPTION IN PLASTIC FOAMS

Chlorofluorocarbons (primarily F-11 and F-12) are employed as blowing agents in the production of plastic foams made from polyurethanes, polystyrene, and polyolefins. These compounds are used, either as the primary blowing agent in styrene and polyethylene foams or as an auxiliary blowing agent in urethanes, to form the cellular structure of these foams. Other types of plastic foams (primarily urea, phenolic, vinyl, and epoxy foams) are produced in much smaller volume, and do not typically involve the usage of chlorofluorocarbon blowing agents.

The 1975 consumption of chlorofluorocarbons as blowing agents is estimated to be 80 to 84 million pounds, roughly 9% of total U.S. production for 1975. Flexible and rigid urethane foams together account for more than 90% of total usage of chlorofluorocarbons as foam blowing agents. Rigid urethane foams consume substantially greater quantities of these compounds than are used for flexible urethane foams. However, chlorofluorocarbon emissions from flexible foam are many times greater than those from rigid foams.

The primary reason for this discrepancy is that blowing agent vapors are largely retained within the rigid urethane foams, while all of the blowing agents used for flexible foams diffuse to the atmosphere promptly after foaming.

Because chlorofluorocarbon consumption for plastic foams is dominated by the two classes of urethanes, major attention will be directed toward emissions and possible emission control systems for the urethane foams, with less detailed consideration of styrene and olefin foams.

To ascertain the extent to which it may be feasible to control chlorofluorocarbon vapor emissions in foam production, it is necessary to examine each of the major foam production processes. The practicality of achieving significant reductions in the quantity of blowing agents discharged to the atmosphere depends largely on how much chlorofluorocarbon vapor is lost from various production stages in different foaming technologies, and the extent to which these vapors can be collected for processing or recovery.

An analysis of chlorofluorocarbon losses has been performed for those foaming processes accounting for nearly all current production of urethane foams:

* Flexible slab foams;

* Flexible molded foam shapes;

* Rigid boardstock and billets;

* Rigid foam core panels;

* Rigid foam and froth cavity filling (in-plant); and

* Rigid foam applied on job-site.

In the sections which follow, the main features of each process which affect the quantity of chlorofluorocarbons emitted from foams will be highlighted with emphasis on the practicality of collecting these vapors for subsequent treatment or recovery. To aid in comparing chlorofluorocarbon consumption and emissions, a "model plant" will be defined for each of the six types of foam processes. These plants are intended to typify current industrial practice on average size or larger, fairly modern production lines. Although it is patent that one model cannot reflect the wide range of commercial conditions for an entire segment of the foam industry, we believe the use of these model plants can help to clarify both technical and economic aspects of chlorofluorocarbon emission control systems.

FLEXIBLE URETHANE FOAMS

Three times as much flexible urethane foam is produced annually as rigid foams. Most flexible urethane foam is produced by fairly large firms utilizing high capacity, continuous production lines.

Approximately 70% of flexible foam is produced by the continuous slab or bun stock process (see Table IV-1), while the balance is fabricated by molding into specially shaped and cored parts. Substantially all of carpet underlay, textile and clothing laminating foams, and mattresses and bedding are produced as slab stocks. Furniture seats and cushions require molded shapes as well as cut sheet foams. Automotive foams span a wide range, typically involving sheeting for door padding, deep molded seating, and medium density crash padding for dash, sun visors and head rests. Some of this foam is purchased from major producers, but over 50% of automotive foams are captively produced in the body plants where they are used.

Table IV-1. 1975 FLEXIBLE URETHANE FOAMS, ESTIMATED PRODUCTION BY FOAMING PROCESS

		1975 Consumption (million lb)			
Application	% Slab	M.P.	Slab	Mobay	Slab
Bedding	90	136.4	122.8	142	127.8
Furniture	80	352.0	281.6	447	357.6
Carpet underlay	100	30.8[a]	30.8	93[b]	93.0
Transportation	50	341.0	170.5	320	160.0
Textile laminates (ex. carpet)	100	26.4	26.4	21	21.0
Packaging	80	19.8	15.8	10	8.0
Other	70	17.6	12.3	11	7.7
Total		924.0	660.2	1,044	775.1
Balance molded and other			264.0		268.9
Percentage slab and bun			71.5%		74.2%

---

[a] Prime foam only; excludes 60 million lb prompt scrap and reclaimed foam - foam shredded and rebended to form controlled density resilient padding.

[b] Does not include "bonded" foam consumption.

Source: Estimates based on References 1 and 2.

An approximate distribution by major foam production process is shown in Table IV-1. The two recent breakdowns by end-use differ somewhat with regard to individual applications, but both sources indicate that slab foam processes account for some 72 to 75% of current U.S. flexible urethane foam production.[1,2]

Each of the major processes for producing different types of flexible urethane foams, i.e., continuous slab stock and molded shapes, possess characteristics that influence the degree to which chlorofluorocarbon emission controls may be technically feasible. These two types of production lines will be briefly described. For each process these characteristics will be incorporated into a representative "model plant" and will be specified as one basis for considering the applicability of various types of emission control systems.

Flexible Urethane Slab

Production of Flexible Urethane Slab - The manufacture of flexible urethane sheet or slabs is performed on continuous production lines requiring extensive specialized facilities. Typical producers include the major tire and rubber firms, chemical companies, and large furniture and mattress companies. Virtually all of these large volume producers make or purchase the basic ingredients, and create their own formulations to generate foams employing the "one-shot" mixing process.

Much of the success of urethane foam production is related to the development of reliable mixing and dispensing equipment, together with sophisticated material handling systems. A typical flexible foam line employs high production rates, dispensing reactants at 150 to 1,000 lb/min, and the complete foam line is often over 200 ft in length. A general plan layout for a flexible slab foam plant is shown in Figure IV-1.[3]

Plant facilities which relate to chlorofluorocarbon handling comprise:

- Unloading track and dock,
- Transfer pumps, hoses, lines,
- Bulk storage tanks (pressurized),
- Pre-mixing and blending weigh tanks,
- Recirculating or stirred dispensing tanks,
- Dispensing unit and control system,
- Primary foaming conveyor and tunnel,

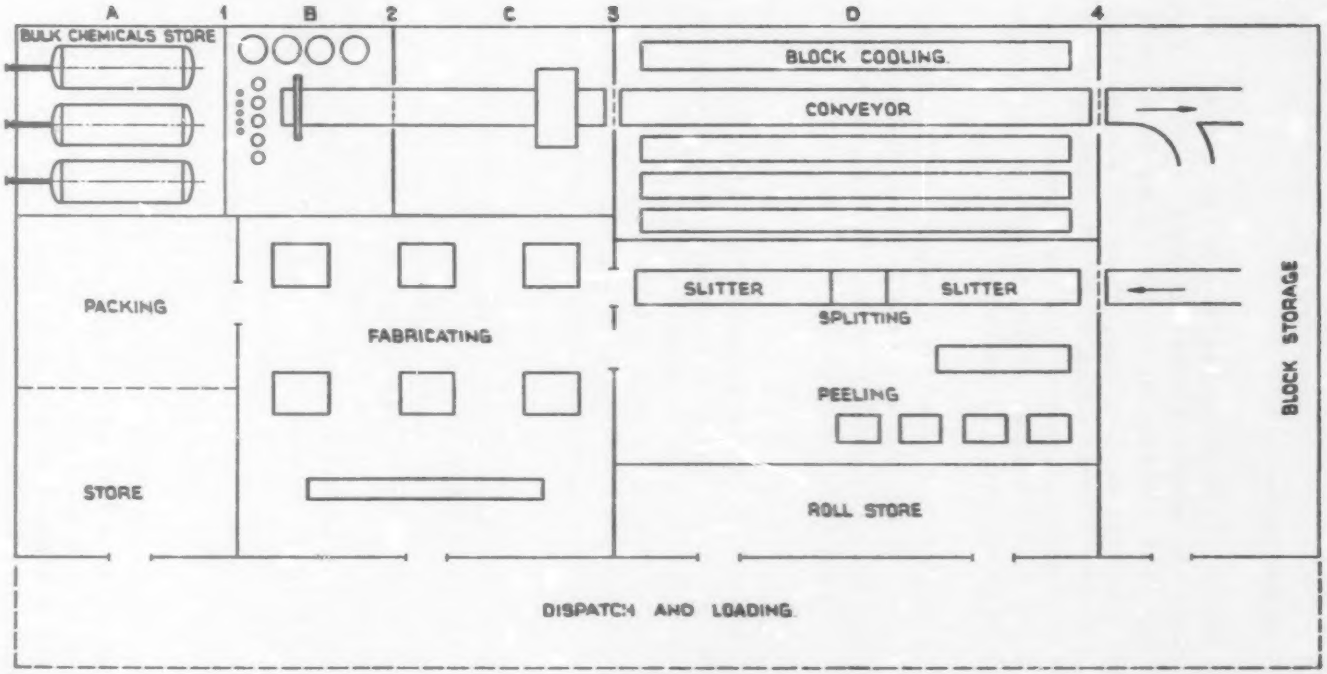

A
1
B
2
C
3
D
4
BULK CHEMICALS STORE
BLOCK COOLING
CONVEYOR
SLITTER
SLITTER
SPLITTING
PEELING
BLOCK STORAGE
PACKING
FABRICATING
STORE
ROLL STORE
DISPATCH AND LOADING

Figure IV-1. General plan for flexible slab foam plant

- Secondary bun conveyor to cut off and trim saws,
- Take-off conveyor to storage area, and
- Storage and aging racks.

In commercial continuous-slab production by the one-shot process, the reactants are pumped by accurate metering pumps (± 0.5%) from the storage tanks, through heat exchangers, to the mixing head. Most systems employ three-way valving at the head, which allows material streams to recirculate back to the storage tanks or be diverted into the mixing chamber of the dispensing head. Storage tanks are usually pressurized with dry nitrogen so that chlorofluorocarbon vapors do not escape and moist air is not allowed to enter the tanks.

The mixing head allows each chemical stream to recirculate, or enter the mixing chamber at exactly the same instant. Complete mixing within the dispensing head can be achieved by (1) high-speed rotating mixers, (2) static or helical mixers, or (3) high-pressure stream impingement mixing.

In the most widely employed bun process, the mixed reactants flow from the mixing head and pour onto a continuously moving belt or web of release paper, so that a foam loaf is formed as the reaction takes place. This bun loaf is usually 6 to 8 ft wide and rises 2-1/2 to 4 ft high, depending on foam density and throughput. Wide, high-rise buns maximize the amount of prime, uniform foam, with the least amount of side and top skin trim.

Two basic methods are employed to generate the foam loaf. Most commonly, the mixing head is mounted on a traversing bridge which moves the head (or heads) back and forth at right angles to the foam conveyor so that overlapping parallel lines of liquid are laid down. The primary foaming conveyors range from 50 to 100 ft in length and travel at speeds from 12 to 20 ft/min. Near the dispensing point, the conveyor line slopes downward some 5 to 10 degrees to prevent the liquid mix from falling into the rising foam. Typically, the foam is dispensed onto a paper sheet which moves along with the conveyor. The conventional traversing foam system is illustrated in Figure IV-2a.[4/]

More recently, fixed dispensing heads have been arranged to deliver reactants to the bottom of a V-shaped trough where the foam rises to the top before contacting the sheet of release paper. Since the reactants are delivered beneath a blanket of expanding foam, there is less immediate loss of chlorofluorocarbon blowing agent and other volatiles. Delivery of

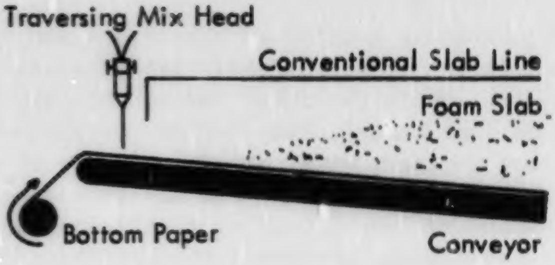

Traversing Mix Head
Conventional Slab Line
Foam Slab
Bottom Paper
Conveyor

Figure IV-2a. Schematic of traversing foam head machine

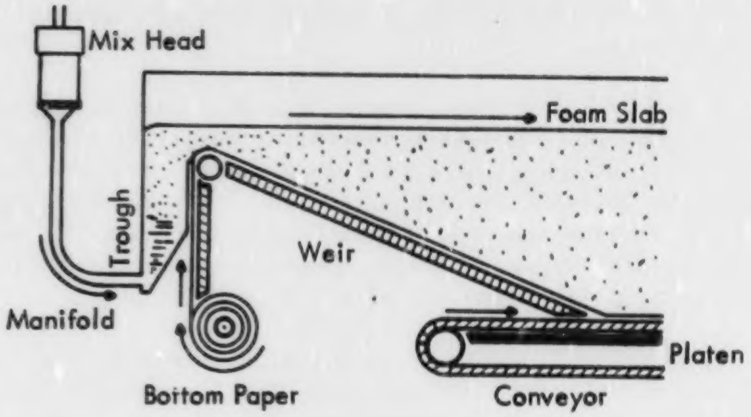

Mix Head
Foam Slab
Trough
Weir
Manifold
Platen
Bottom Paper
Conveyor

Figure IV-2b. Stationary head, foam trough machine

reactants beneath the foam surface is claimed to achieve slightly greater foam height from mixtures employing the same CO_2 and chlorofluorocarbon blowing agents. This type of foam generation is schematically shown in Figure IV-2b.[5]

The primary foam generating section of all slab lines is fairly well enclosed to prevent the escape of highly toxic isocyanates. Openings are provided at the pour point, while the other end of the foam tunnel is usually open. Within the foam tunnel, the slab may be subjected to radiant or steam heat to cure the surface. After several minutes of curing (typically 10 to 15 min), the foam is tack-free and can be handled. The continuous pour is cut into standard length buns to facilitate handling, trimming, and cutting into the desired thickness sheets. These shorter length buns (10 to 60 ft) are usually allowed to cool, age, and cure for 12 to 24 hr before being fabricated into the desired product. Standard types of flexible foams include slit sheet, convoluted or contoured slab, and thin-peeled sheets for flame lamination to textiles. Textile laminating foams are usually of the polyester type, while the preponderance of flexible foam is of the polyether type.

Although a fairly wide range of flexible foams may be produced by continuous slab foaming, the vast bulk of production lies in the low and medium density, soft to firm range. Polyether foams are much more widely produced than polyester formulations for continuous slabs. Some foams are blown exclusively with the CO_2 generated from the reaction of isocyanates with free water.

Softer foams with different indentation load characteristics are produced by incorporating volatile liquids as auxiliary blowing agents. Most commonly F-11 is used, although methylene chloride may also be employed. Thus, the chlorofluorocarbon content of the reactant liquid dispensed onto the conveyor may range from 0 to perhaps 22% by weight for the "extra supersoft" grade. The most common range of chlorofluorocarbon content is from 8 to 14% by weight of all ingredients.

For purposes of calculating F-11 emissions and potential controls, a typical low density, soft, one-shot polyether formulation will be assumed. Table IV-2 shows both a water blown formulation, a flame resistant foam, and the standard F-11 blown foam composition.

A model plant for the production of flexible polyether slab foam is described in Table IV-3.

Table IV-2. TYPICAL ONE-SHOT FLEXIBLE FOAM FORMULATIONS

Ingredient	Standard 1.4 pfc FC blown[7]	Water blown medium-density foam slab[8]	Self extinguishing foam[6]
Polyether triol	100	100	100
Isocyanate	42.5	42.5	43.5
Water	3.5	3.3	3.5
Tin catalyst	1.75	0.45	0.40
Amine catalyst(s)	1.0	0.45	0.09
Flame retardant	-	-	15.0
Silicone surfactant	2.0	1.0	1.6
Fluorocarbon-11	13.5	-	9.0
Total	168.5	147.7	173.1
Fluorocarbon percent	8.0	0.0	5.2
Blowing loss (CO_2, H_2O, FC)	22.0	8.05	17.5
Foam yield (%)	86.9	94.5	89.9
Foam density, lb/ft^3	1.40	1.80	1.50

Table IV-3. MODEL PLANT - FLEXIBLE POLYETHER SLAB FOAM

1. Continuous pour bunstock machine. Foam line operated 6 hr each production day. Foam produced 65 days per year.

2. Pour rate - 450 lb/min; 162,000 lb liquids per day.

3. Foam profile - 7 ft wide, 42 in. high (24.5 ft^2 section).

4. Foam density - Cured bun before trim; 1.54 lb/ft^3.
   Trim 1 in. of 3 lb/ft^3 crust; loss of 3.5 lb/lineal ft.
   Final trimmed foam, 1.40 lb/ft^3.

5. Foam system - Standard, open-cell polyether one-shot.
   Water 3.5 per 168.5 = 2.1% by weight.
   Fluorocarbon 13.5 per 168.5 = 8.0% by weight.

6. Speed of primary foaming conveyor = 12 ft/min

$$\frac{450 \text{ lb/min}}{1.54 \text{ lb/ft}^3} \div 24.5 \text{ ft}^2 = 11.93 \text{ ft/min}$$

7. Foam tunnel enclosure - 60 ft long x 6 ft high x 8 ft wide.
   Opening at pour end - 8 ft x 3 ft high.
   Discharge end open - 8 ft x 6 ft high.
   Face velocity at openings $>$ 250 cfm/ft^2 of opening.
   Fan required 20,000 scfm.

8. Transfer conveyor - 60 ft long to cut-off saws.
   Ventilation by overhead hood with plastic side curtains.
   Fan required 10,000 scfm.

9. Cut-off saw and take-out conveyor - 60 ft long to storage.
   Ventilation by overhead hoods.
   Fan required 15,000 scfm.

10. Foam storage area - 128 ft x 40 ft x 21 ft high.
    Ventilation at 4 cfm/ft^2.
    Fan required 20,000 scfm.

11. Foam yields

CO_2 loss	8,300 lb/day	(450 x 0.021 x 2.44 = 23 lb/min)
FC loss	12,960 lb/day	(450 x 0.08 = 36 lb/min)
Trim loss	15,032 lb/day	(3.5 lb/ft x 11.93 ft/min = 41.8 lb/min

Blowing agent losses	21,260 lb/day; 86.9% bun yield, 140,740 lb/day
Total weight loss	36,292 lb/day; 77.6% final foam, 125,708 lb/day

Chlorofluorocarbon Losses - Well designed foam plants making continuous slab stock usually show exceedingly small chlorofluorocarbon losses in transfer and handling. No data are available to suggest that inadvertant vapor losses would exceed 0.5% of the total amount used. For the model plant using 12,960 lb of F-11 per day of foam production, losses could average 60 to 70 lb/day. Some additional losses are associated with cleanup. Methylene chloride is often used as the solvent to flush short sections of the lines and the dispensing head, and to dissolve splashes of partially cured polymers.

All of the chlorofluorocarbon blowing agent dispensed from the mixing head is lost from flexible foams within a short time. The ingredients are usually dispensed at approximately 25 to 28°C, or a few degrees above the normal boiling point of F-11. Thus, vaporization and loss of chlorofluorocarbon blowing agents begins immediately upon discharge from the mixing head. Depending on the formulation, a "foam line" will be formed about 10 to 12 in. beyond the pour point where the foam begins to rise. The heat of reaction volatilizes the F-11 almost completely before the maximum internal foam exotherm is reached. Maximum temperatures typically occur after 4 to 5 min (about half-way through the foam tunnel). The loss of chlorofluorocarbons exert a cooling effect so that temperatures within flexible foam buns seldom exceed 190 to 225°F. Additional heat may be supplied to cure the top skin to a tack-free condition.

In the model plant, foam is formed at the rate of 292 ft^3/min. The polymer structure of the foam occupies from 2.4 to 3% of the apparent foam volume, with 96 to 97% vapor volume within the cells. The standard formulation employed generates 126 ft^3 of F-11 vapor, plus 252 ft^3/min of CO_2 at maximum exotherm of 200°F. The combination provides a total blowing agent vapor volume of 378 ft^3/min. Thus, nearly 86 ft^3 of excess vapor is forced from the open cell foam each minute at about the midpoint of the foam tunnel.

Unfortunately, there is virtually no information in the technical literature on urethane foams to indicate either the quantity of blowing agent lost from foams or the concentration of blowing agent vapors in the hoods or exhaust air. One source estimated that perhaps 80% of the F-11 had evolved from the flexible slabs by the time it left the cut-off saw (about 120 ft or 15 min after foaming).[9/]

It appears that very few investigators have attempted to analyze chlorofluorocarbon concentrations associated with foam production. Ward,[10/] in 1975, measured F-11 vapors in several urethane foam plants. Samples were only taken in the breathing air occupied by plant personnel. Because all the plants were working with the relatively toxic isocyanates, good ventilation is necessary. As seen from Table IV-4, concentrations of F-11 ranging from 15 to 586 ppm were measured. For a high production slab line typified by the model plant (Table IV-3), vapor concentrations near the foam machine average about 170 ppm. These concentrations are all well below the accepted TLV of 1,000 ppm for F-11. Chlorofluorocarbon vapors are much heavier than air and tend to sink to and collect near the floor level. In many plants, schlieren discloses streams of F-11 vapors drifting down from equipment and floating across the floor.

Table IV-4. FLUOROCARBON 11 CONCENTRATION IN BREATHING ZONE AIR OF FOAM MANUFACTURING FACILITIES[10]

	FC-11, ppm v/v[a]			
	Flexible foam			Rigid foam
	High production rate	Normal production rate		
Location	regular foam	Regular foam	Supersoft, foam	Panel production
Mix tanks	NA	NA	NA	52
Foam head	178	62	88	113
Expansion - begin	146	31	139	94
- middle	182	25	198	147
- end	181	24	156	192
Cutting	181	15	130	64
Curing racks	355	280	586	NA
Product storage	NA	10	10	12
General building	61	26	47	70
Packaging/shipment	95	10	10	30
Laboratory/office	61	26	47	60

Note: NA - Not available, e.g., no curing racks, tanks outside, etc.

a/ All measurements from corrected POVA readings. Agreement with grab samples typically within ± 5%.

For purposes of further analysis it will be assumed that 50 to 60% of F-11 vapors are evolved from flexible foams by the end of the foam tunnel; 75 to 80% of F-11 is lost by the cut-off saw; 5 to 10% more is lost in conveying to the storage racks; and all but 1 or 2% of the F-11 is dissipated from the foam during aging before splitting. The remaining 1 or 2% is sorbed or dissolved in the polymer, and will be lost to the air within a few weeks.

What fraction of these chlorofluorocarbon vapors are picked up by the hoods and ventilation systems that currently are employed? To date there is no satisfactory answer to this key question.

Dr. John Backus of Mobay reported that analyses undertaken in July 1976[11/] gave somewhat puzzling results for F-11 concentrations at various points within the foam line and ventilation system. The mass balance of F-11 did not agree with chromatographic measurements on grab samples taken from the line. Most points sampled showed only a few hundred parts per million of F-11, while the highest concentration encountered (3,000 ppm) was at a low point in the conveyor. This concentration is lower than would have been expected if a sizable fraction of the chlorofluorocarbons are evolved in the first 8 to 10 min of foam formation. Exhaust air concentrations apparently were also significantly lower than anticipated.

Note: Additional analyses made since the first draft are now able to account for about 70% of the chlorofluorocarbon dispersed from the foam head. Roughly 60% of the total is going into the ventilation ducts; some 10% more or less is retained by the foams, past the cut-off saws, and into the storage area. Mobay engineers and chemists generally believe that, with suitable redesign of the foam facility, it should be possible to collect up to 80% of the blowing agent vapors for some form of treatment.

Clearly, more detailed measurements need to be obtained before it is possible to specify the extent of engineering modifications that would be required. The air flow rate must be significantly reduced to make any form of chlorofluorocarbon recovery system practical.

Two possible explanations for the lower than expected chlorofluorocarbon concentrations seem equally likely:

1. F-11 diffuses out of open cell foams slower than has been generally accepted, and the bulk of chlorofluorocarbon is retained within the foam cells until well beyond the cut-off saw and into storage.

2. The F-11 vapors are lost from the foam buns, but settle to low points of the conveyor or tunnel and are partly lost through gaps and openings in the conveyor system. This latter theory would partly explain the 170 ppm of F-11 found in the work space near the foam line. If the chlorofluorocarbons are evolved from the foam buns within the main tunnel, the overhead hoods and exhaust ducts may not be effective in capturing these heavy vapors. Further study is indicated to clarify the distribution of blowing agent emissions during foam production.

Molded Flexible Urethane Foam

The second largest source of chlorofluorocarbon emissions from plastic foams is associated with the production of molded shapes and urethane parts for furniture, automotive seats and cushions, and resilient padding. In 1975, it is estimated that 265 million pounds of molded components and parts were produced (see Table IV-1). Chlorofluorocarbon consumption was in the range of 14 to 18 million pounds, all of which may be considered to diffuse into the atmosphere within a few weeks or months.

Molded shapes are produced both by high volume fabricators such as Fisher Body, Kroehler Furniture, and Ford Motor Company, and also by a large number of custom molders whose production runs may be fairly small. None of the molded furniture and automotive production lines begin to approach the volume of foam produced on continuous slab foam lines.

In addition to the smaller volume of foam produced per plant, several other characteristics of molded foam production distinguish molding from slab production. While most large producers prepare formulations from basic ingredients and mold one-shot foams, some of the smaller molders rely upon quasi-prepolymers and complete packaged liquid urethane systems furnished by compounders.

Foams are dispensed intermittently from the mixing heads into molds, rather than sustaining a continuous pour as required for slabs. This is true whether one-shot or prepared reactants are employed. In order to deliver the required charge for a chair cushion or auto seat into the mold rapidly so that the mold can be closed before the foam starts to rise, pour rates are often fairly high, i.e., 150 to 750 lb/min.

Until about 1969, the technology for foam molding generally utilized the "hot molding" process. Molds were conveyed on pallets through a pre-heating oven, to the foam dispensing head, where the operator discharged the reactive mixture into the warm mold. The mold was closed (either manually or automatically by cams along the conveyor line) and conveyed through a curing oven. After the appropriate cure time, the molds were opened and the foam parts de-molded at the strip-out point.

Within the past 5 or 6 years many molding operations have switched to the so-called cold molding process. More highly catalyzed systems are employed which are capable of complete cure without requiring a curing oven. The molds are still pre-warmed (largely to minimize surface skin formation that would occur if poured into a cold mold), and the foam rises and cures without additional heating. The introduction of deep molded cushions for automotive seating, which replaced the assembly of springs, cushion and topper pad, began with the 1971 model year. Today, most automobile seats are produced by molding the spring wires directly into deep foam cushions.[12/]

Chlorofluorocarbon Consumption in Molded Foams - Because of the diversity of molding operations it is difficult to define any "typical" plant. However, several features relating to atmospheric emissions of chlorofluorocarbons can be identified.

Due to the smaller size of the average molded foam plant, somewhat higher losses incident to handling are to be expected. In many instances up to 1% of the chlorofluorocarbons consumed for foam blowing may be lost in transfer and mixing prior to dispensing the foam.

Many current mixing heads for molding require a chlorofluorocarbon flush before and after dispensing each charge of reactants. This is called lead time, and lag time. For periods of 1 to 3 sec before and after dispensing the predetermined quantity of ingredients, chlorofluorocarbon vapors are vented through the head. Up to 5% of the total F-11 consumed can be vaporized in this way directly at the mixing head.

Effective removal of isocyanate vapors from the air near molding lines is required to meet existing health and safety regulations. Because the discharge of heavy chlorofluorocarbon vapors tends to cause all volatiles to fall, it is standard practice to provide local or spot ventilation ports below and behind the dispensing point to scavenge a large percentage of the toxic isocyanate vapors from the area of the dispensing head.

In the most elaborate and modern plants producing large parts, it is customary to employ a computer control console which can provide rapid variation of the foam formulation to accommodate molding a variety of parts. Successive pallets may, for example, present molds for six arm rests, four padded sun visors, two bucket seats, four head rests, two seat backs, and one bench seat for an automobile. In some cases, graded density parts are molded by delivering a series of pours, containing different percentages of blowing agents, into various portions of a single mold. It is common to adjust foam density and firmness by varying the blowing agent content--even to the point of changing the formulation "on the fly."

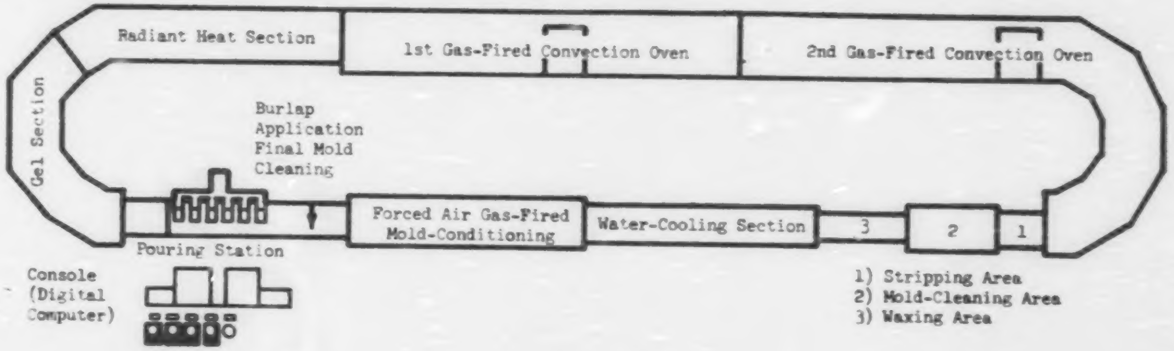
The highly catalyzed mixtures cream almost as soon as delivered into the warmed mold. Once the mold is closed, the only source of chlorofluorocarbon emissions is the gradual displacement of air and vapor through the vent holes as the foam fills the mold cavity. Once foam has plugged the vents, little or no F-11 is emitted until the mold is opened after curing.

For molded shapes, the strip-out point is a major source of blowing agent emissions.[13/] Despite the best release coatings, it is often necessary to stretch or compress the freshly made part in order to de-mold it. Here again, ventilation ports are located below the de-molding station. In the cold molding process, the parts are usually subjected to a postcure heat treatment using radiant heaters for about 1 hr after de-molding. Additional F-11 diffuses out of the foam parts as they are postcured, followed by cooling before trimming. In certain types of molded parts, closed cell foams or incompletely open-cell foams may retain a significant fraction of the total F-11 vapor generated during foaming. Eventually, all of this chlorofluorocarbon will diffuse out of the flexible polymer. Some parts containing closed cells are subjected to compression or flexing to crush these cell walls, releasing vapors.

A schematic diagram of a hot-molding line is shown in Figure IV-3. A model flexible urethane foam molding plant is described in Table IV-5.

Chlorofluorocarbon Emissions in Molding Flexible Form - Information regarding the rate of diffusion of chlorofluorocarbons out of molded flexible foams is virtually nonexistent. Because of the large number of molding plants, and their great diversity, no meaningful measurements of F-11 concentrations have been made, either for breathing air or exhaust air streams. We have therefore accepted the best personal estimates of experienced foam molders, and of molding equipment suppliers.

For the model foam molding line, each 8-hr shift dispenses a total of 11,520 lb of urethane system. Since the formulation incorporates 6.5% by weight of chlorofluorocarbon, consumption in foam is 749 lb/shift. Blowing losses of CO_2 and chlorofluorocarbon are 10.9% for a molding yield of 89.1%. Rejected parts and trim scrap are 4% and 2%, respectively. Per shift, each line molds 5,400 parts.


Radiant Heat Section
1st Gas-Fired Convection Oven
2nd Gas-Fired Convection Oven
Gel Section
Burlap
Application
Final Mold
Cleaning
Forced Air Gas-Fired
Mold-Conditioning
Water-Cooling Section
3
2
1
Pouring Station
Console
(Digital
Computer)
1) Stripping Area
2) Mold-Cleaning Area
3) Waxing Area

Source: Reference 3.

Figure IV-3. Schematic layout of a flexible urethane foam molding line ("hot-molding" depicted)

Table IV-5. MODEL FLEXIBLE URETHANE FOAM MOLDING PLANT

1. Molding lines operate 8 hr/shift. Pallet conveyor delivers two molds per pallet to foam head. Pre-warmed molds used without cure oven, i.e., cold molding. Plant operates 230 days per year.

2. Dispensing head is capable of 300 lb/min, and maintains accuracy down to 60 lb/min. Mixing cavity volume is 4 $in.^3$. Lead and lag of 3 sec for fluorocarbon flush.

3. Two molds are filled each 30 sec. Average charge requires 12 lb for the two molds.

4. Foam formulation contains 1.8% water by weight. Differing proportions of F-11 are introduced at the head to vary the softness and density of foam parts. Average F-11 concentration for all parts is 6.5% by weight.

5. Pouring station ventilated by 2 x 6 ft rear port, extending below conveyor an additional 3 x 6 ft. For 300 cfm/ft^2, fan required ~ 10,000 scfm.

6. No hood or ventilation provided over conveyor during 16 min cold cure.

7. Stripping area ventilated by rear wall and under conveyor plenum totalling 24 sq ft in area. For 200 cfm/sq ft, fan required ~ 5,000 scfm.

8. Molded parts of each type are placed in wire baskets on 50-ft roller conveyor for 1 hr post-cure. Heating tunnel over conveyor with air plenum beneath conveyor. Effective opening area, 50 sq ft. For 100 cfm/sq ft, fan required 5,000 scfm.

9. Parts are allowed to cool for 30 min before inspection and trim. No ventilation provided. Some parts are roll-crushed to open closed cells. If crushing is performed, the post-cure ventilation system collects a large part of the vapors.

The best available approximations of chlorofluorocarbon losses from the molding process suggest that losses based on total mix poured average:

- 1 to 1.5% F-11 lost in handling and mixing systems prior to molding.
- 8 to 10% F-11 vaporized dispensing mixture into molds (add ~ 5% more if F-11 flush of head is used).
- 3 to 5% displaced as foam rises to fill mold (includes any losses during closed mold cure for cures not employing curing ovens; add 5% if oven cure is used).
- 25% of F-11 released at de-mold station.
- 40% evolved during post-cure of 1 to 2 hr (deduct 5% if oven curing is used).
- 15% expressed from foam when flexed or roll compressed to open closed cells.
- 5 to 7% residual F-11 remains in foam, and will diffuse out within 10 days.

Thus, for a molding line consuming 749 lb of F-11 per 8 hr shift, the estimated chlorofluorocarbon losses at various stages of molding would be distributed as shown in Table IV-6.

Other Flexible Urethane Foam Processes

In addition to foam slab production and foam molding, there are a few other important classes of flexible urethane foams.

Urethane foam has almost displaced hair-jute padding and waffle latex foams in carpet underlay. The rise of this market has been so rapid that accurate estimates of production for this use are not available. In 1975 consumption of prime foam for carpet padding probably exceeded 30.8 million pounds.1/ There are doubts over the Mobay estimate of 93 million pounds.2/ In addition, some 60 to 70 million pounds of rebonded foam was produced for underlay.1/

Table IV-6. DISTRIBUTION OF CHLOROFLUOROCARBON LOSSES, MOLDED FOAM
(Basis: 1,520 lb of liquid urethane poured per shift)

Processing stage	Estimated annual losses (lb)
F-11 lost in materials handling*	2,583
Charging molds	17,222
Chlorofluorocarbon flush*	8,611
Foam rise and cold cure	8,611
De-molding station	43,056
Post-cure } (may be	68,890
Crush rolls } combined)	25,834
Remaining in foam parts	8,611
Total emissions	183,418

Note: Losses marked * are in addition to the 749 lb F-11 per shift dispensed as foam ingredients.

Many carpeting manufacturers apply urethane foams directly to the back of needle-tufted carpets using carefully controlled foam extrusion. Roto-vinyl yard goods and other "hard" floor coverings also are produced with thin, high-resiliency urethane foam backings. Depending upon the composition of the carpet underlay foam, widely varying figures are obtained for consumption.

We believe that total current output of floor cushioning foams is about 100 million pounds, or nearly 10% of U.S. production of flexible urethane foams. Because these foams are processed in large volumes using continuous lines, the technology is fairly similar to flexible slab foam production. Lacking valid data on corresponding chlorofluorocarbon usage and losses, carpet and other floor covering cushions will be treated as a part of continuous slab foaming for purposes of analysis.

Specialty foams produced in relatively low volumes amount to some 10 million pounds annually. Scant information is available concerning reticulated flexible foam, self-skinning flexible urethanes, reinforced flexible foams, and medium density, impact-absorbing, low-resiliency padding. These foams consume relatively small amounts of chlorofluorocarbons, and will not be analyzed in detail. For convenience, these foams will be considered as part of molded foams.

RIGID URETHANE FOAM PRODUCTION

In 1975 rigid urethane foam production reached 340 to 383 million pounds. This represents only 25 to 30% of the combined total for flexible and rigid urethane foams. The approximate distribution of rigid foam for the latest year is shown in Table IV-7.

Table IV-7. U.S. RIGID FOAM CONSUMPTION - 1975
(millions of pounds)

	Modern Plastics[1/]	Mobay[2/]
Building construction	176.0	133
Refrigeration appliances	72.6	70
Transport carriers	48.4	36
Industrial (tank and pipe)	15.4	44
Total thermal insulation	(312.4) 81.6%	(283) 83.2%
Furniture parts	35.2	20
Packaging	13.2	12
Marine and flotation	13.2	10
Miscellaneous	8.8	15
Total	382.8	340

More than 80% of all rigid urethane foam is used as thermal insulation. Chlorofluorocarbon blowing agents are considered essential to attain satisfactory insulating foams. Therefore, more than two-thirds of the total chlorofluorocarbon consumption for plastic foams is used to produce rigid urethanes.

By far, the largest use of rigid urethane foams is in building construction. There has been a substantial increase in rigid foam use since the cost of energy has risen sharply, and the concern for energy conservation has grown. Other important insulating uses include refrigerators, freezers, transportation carriers (truck trailers and freight cars) and industrial applications such as the insulation of tanks and pipelines. For insulation uses, urethane foams are typically produced at densities of 1.6 to 2.2 lb/ft^3 (pcf); and virtually all of the insulating foams employ chlorofluorocarbon blowing agents.

Other uses of rigid urethane foams (e.g., packaging and dunnage, boats and flotation, and molded structural parts) may or may not employ chlorofluorocarbon blowing agents. In particular, the medium to high density (8 to 26 lb/ft^3) rigid urethane moldings have grown rapidly in application between 1967 and the present. These molded parts replace wood in furniture, television cabinets, decorative interior profiles, and a variety of industrial parts. In the higher density ranges little or no chlorofluorocarbon blowing agents are employed.

Because of the diversity of uses for rigid urethane foams, a wide range of processes and techniques for production have been developed. Only those processes that employ chlorofluorocarbon blowing agents will be considered.

Since no detailed statistics on production in different forms are regularly collected, there is considerable uncertainty regarding the proportion of rigid foams produced by different processes. By pooling estimates obtained from trade sources, broad estimates of current output for four major categories of rigid foam production have been derived.

For purposes of analysis, the data below lists the four types of rigid foam processes that will be discussed. Estimated production for 1975 is given for each category both in millions of pounds, and as a percentage of total rigid urethane foams (excluding high density furniture foams).

APPROXIMATE DISTRIBUTION OF RIGID URETHANE FOAMS BY PRODUCTION PROCESS

Foam type	1975 Output (million lb) 2/ 1/	Rigid foam (%)[a]
Boardstock, slab, billets, logs	96-127	28-33
Structural foam core panels	42-57	12-15
Foam-in-place cavity (in-plant)	106-128	31-33
On-job-site foam application	36-48	11-13
All rigid foam[a]	280-360	82-126
Reported by trade[a]	320-348	

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a/ Furniture structural foams excluded.

Reaction injection molding of furniture parts and other high density "structural" foams will not be considered because the use of chlorofluorocarbon blowing agents for high density foams is insignificant. A small volume of low density rigid urethane foam is produced by molding to shape. Typical uses include pre-formed pipe lagging, imitation wood beams or moldings, and packaging applications. Production processes are sufficiently similar to boardstock that these molded parts will be treated as part of slab and billet production.

Each of the four types of production techniques possess many similar aspects, plus certain features directly related to chlorofluorocarbon consumption and atmospheric emissions.

Rigid urethane foams are prepared by mixing two or more reactive liquid ingredients together. The chemical reaction which results forms a polymeric material which entraps gas bubbles to provide the desired cellular structure. The gas required for foaming is derived from carbon dioxide released during the polymerization reaction, or from the volatilization of an added blowing agent vaporized by the heat of reaction.

For rigid foams, standard practice is to formulate "liquid systems" which require the mixing of only two or three streams at most. Large volume producers purchase basic ingredients and prepare their own systems. Many smaller foam producers prefer to purchase prepared liquid systems offered by a number of resin compounders.

The liquid ingredients are mixed in a foam machine with a pumping unit capable of accurately metering the components through a continuous mixer which blends the components uniformly. Preparation of the urethane system components, metering and complete mixing are all critical to the proper manufacture of polyurethane foams. Machinery for the proportioning and dispensing of urethane foams is highly developed, with equipment being offered by 48 manufacturers. The basic forms and variations among commercially available urethane foaming machinery has been reviewed recently by Johnson,[14/] and will not be considered in detail. After the mixture is dispensed from the metering and mixing head, the method of application, and the means used to contain the foaming mixture, differ widely according to the application. These factors in turn influence the choice of blowing agent and the formulation of the urethane system.

Rigid urethane foams can be manufactured by batch processes, by a continuous slab or "bun" process, by foaming or frothing in place, and by spraying. The four basic dispensing methods for rigid urethane foams are pour, froth, spray, and injection. Molding and casting are both generally considered as a form of foam pouring. The frothing process can be applied either to foam pouring, or froth spraying. Thus, the basic dispensing methods can be divided into two broad classes--spraying and pouring.

In the U.S., the continuous slab production and foaming in place are the most common. Continuous production of rigid foam board stock (commonly used for building insulation) involves pouring the liquid mixture as a thin layer onto a continuously moving conveyor where it expands to form a continuous block of foam. After oven curing, the foam may be sliced to specific thicknesses by a variety of sawing methods. An alternative of increasing importance involves panel production through the continuous application of surface skins (metal, paper, or plastic laminates) with the panel expanding to standard thickness. Foaming in place involves pouring the liquid mixture of foam components from the dispensing head directly into a cavity. Details of this process are presented later in the subsection concerning rigid foam-in-place cavity filling.

Sprayed polyurethane foams are often used for on-site application of rigid thermal insulating foams. The liquid urethane ingredients emerge from the mixing head and are sprayed onto the desired surface to expand. As in pouring operations, froth spraying has become a convenient method of achieving the desired urethane thickness and maintaining control over the desired density and skin thickness.

The most important characteristic of many rigid urethane foaming processes is that the blowing agent vapors are trapped and retained in the finished foam, with only minor losses of chlorofluorocarbon vapors during production. The exact quantity of blowing agent losses depends upon foam stability during rise, percentage and type of chlorofluorocarbons used, the peak exotherm temperature achieved within the foam, and the extent of mechanical rupture of foam cells after curing the foam.

Formulations for rigid urethane foams typically contain from 12 to 16% by weight of chlorofluorocarbon for foam densities ranging from 1.6 to 2.3 lb/ft^3. Often no water is used, or the moisture content is kept close to zero, so that the insulating foams are primarily expanded by chlorofluorocarbon vapors to achieve low thermal conductivity.

The use of chlorofluorocarbons in concentrations much greater than 6% by weight tends to reduce foam stability during the rise. Since rigid urethane foam systems typically contain about twice as much chlorofluorocarbons as found in flexible formulations, considerable care must be taken in selecting surfactants and other additives to achieve as much foam stability as possible. Even at best, freshly rising rigid foams are tender, and subject to collapse if stressed or disturbed. Collapse of foam bubbles before gelation releases part of the blowing agent vapors.

While trichlorofluoromethane (F-11) is the blowing agent most widely used, some suppliers recommend proprietary chlorofluorocarbon blends that offer a wider range of vapor pressures, and are claimed to generate more uniform and consistent foam structures.

For certain types of high vertical rise foaming, and for many cavity filling operations, froth foam pouring or spraying is common. In addition to the customary F-11, up to 6% of low boiling F-12 is introduced into the foam mixing chamber. When discharged from the mixing head, the foam immediately pre-expands into a froth, followed gradually by further expansion as the heat of reaction vaporizes the F-11.

Blowing agent loss in foaming is also affected by the rate of the polymerization reaction. A slow reaction, with long gel times, permits some cells to collapse, thus reducing foam volume and releasing blowing agents. Extremely reactive foam systems, on the other hand, create high internal foam temperatures. In some cases, excessive peak exotherms result in large internal bubbles, some browning of the polymer, and possible expulsion of blowing agent vapors if the volume of vapor at peak temperature exceeds the available cell volume after gelation.

The four types of rigid foam production processes--boardstock or billets, structural foam core panels, cavity filling, and on-site foam application--are sufficiently similar in most respects, that only those differences which determine or influence the consumption of chlorofluorocarbons, and the distribution of chlorofluorocarbon emissions during production need to be considered.

Model Rigid Urethane Foam Boardstock Plant

Boardstock in planks, sheets, billets, and foam logs, is produced on high volume continuous foam machines quite similar to the ones used for flexible foams. Sometimes the identical line may be used to produce both types of foams. The building supply industry, which generates much of the rigid foam, has evolved into a fairly specialized segment, usually producing rigid foam products exclusively. In 1972, the principal boardstock manufacturers accounted for sales of an estimated 75 million pounds of foam; equivalent to 450 million board feet of product. The substantial increase in rigid foam consumption in building insulation since 1972, probably indicates that some 115 million pounds or 690 million board feet of rigid slab and board were consumed in 1975.

The scope of "boardstock" for purposes of this analysis is taken to include all rigid urethane (and polyisocyanurate) foams produced as slab sheet or billet, without facing substrates (raw board), or employing paper or other permeable skins on the finished foam boards. (Panels having metal, plastic, foil, or other impermeable skins are included with structural panels.) The characteristic parameters of the model boardstock line are shown in Table IV-8.

Chlorofluorocarbon Losses in Boardstock Production - Experienced producers of rigid foam sheets and billets report bun yields of 96 to 99 lb for each 100 lb of liquids dispensed from the mixing head.[15] Blowing agent losses during creaming and foam rise vary with seasonal temperatures; however, an estimate of about 97% yield indicates roughly 2% loss of chlorofluorocarbons plus 1% of CO_2, water, and other volatiles.

This estimate of chlorofluorocarbon loss on the foam machine is entirely consistent with the calculated vapor volume losses for the model foam line (i.e., 141 ft^3 of cell volume will hold up to 36.9 lb/min of the 42 lb/min of F-11 dispensed; equivalent to a loss of 12% of initial chlorofluorocarbons). Chlorofluorocarbon vapor concentrations in the plant air near rigid foaming machines have been measured at 150 ppm, which also indicates that the major source of F-11 losses is near the initial foaming point (see Table IV-4, page IV-12).

There is virtually no further loss of chlorofluorocarbons as rigid foam cools and ages. During this period of time, air and other vapors are diffusing into the foam at a slow rate.

Sawing and cutting foams to size, of course, opens cells and exposes additional surface to the air. Some production lines incur trim and saw kerf losses of 8 to 10% of initial bun weight. At the time of sectioning, foams may be up to 1 to 2 days old, and the foam cells contain approximately 57 to 62 mol % F-11.[16] Therefore, some 4.6 to 6.2% of the chlorofluorocarbon remaining in the foam cells is emitted to the air in cutting and trimming the foam. This is the equivalent to 3.9 to 5.3% of initial chlorofluorocarbon dispensed as foam ingredients.

Summarizing chlorofluorocarbon losses for the model size plant (based on 7,560 lb of F-11 used per shift):

* Material handling	1%	or	76 lb/shift
* Foaming machine	12-14%	or	907-1,058 lb/shift
* Trim and cutting	4-5%	or	302- 378 lb/shift
Total plant losses			1,285-1,512 lb/shift

Table IV-8. MODEL URETHANE FOAM BOARDSTOCK PLANT

1. Plant operates 6 hr/day, 200 days/year.

2. Pour rate, liquids: 150 lb/min.

3. Slab profile: 8 ft wide x 1.25 ft high (10 ft^2 cross section).

4. Foam density: 2.0 lb/ft^3 finished product; 94.5% closed cells.

5. Conveyor speed: 7.5 ft/min in 50-ft tunnel; ventilation rate: 5,000 scfm.

6. Chlorofluorocarbon content: 14.0% by weight (21 lb/min).

7. Foam time: 3 min; tack-free: 4-6 min; cure time: 8-10 min.

8. Maximum exotherm: 260°F at 4-5 min.

9. Foam yield factors:
   97 lb of slab per 100 lb liquids dispensed,
   Blowing losses: 2 lb of FC plus 1 lb H_2O, CO_2, and others,
   Vapor volume of foam cells: 97% of 75 ft^3/min = 72.8 ft^3, and
   Volume of FC vapor retained at 260°F: 68.7 ft^3.

10. Trim and sawing losses = 10% of slab.
    Dust collection system only; no fume ventilation.

Ventilation systems for rigid urethanes are often less stringently designed, because less volatile types of isocyanates are used. Thus, the efficiency with which chlorofluorocarbon vapors from foaming are collected into ducts may be lower than would be typical for a flexible foam production line.

Structural Foam Core Panel Production

Rigid urethane foam is produced in substantial volume as finished or semifinished construction components. The best industry estimates are that from 45 to 60 million pounds of urethane foam consumed in 1975 in the form of pre-manufactured structural foam core panels and building components. Major uses include:

* Curtain wall exterior panels,
* Prefabricated wall modules,
* Exterior and interior doors,
* Roofing,
* Prebuilt warehouses and coolers,
* Truck panels, and
* Steel building components.

The various production methods comprise foam core lamination to structural facings, vertical foam-in-place, horizontal foam-in-place, and continuous laminate production. Lamination of surface substrates over foam stock cores to form structural components represents further processing of boardstock. Both vertical and horizontal foaming-in-place in doors or panels may be treated as a variation on cavity filling operations. This section considers a variation on rigid boardstock production, namely continuous foaming between rigid skins to produce load bearing structural laminates.

Facing materials most often include coil steel, embossed or prefinished aluminum, hardboard, plywood, cement-asbestos board, gypsum drywall board, reinforced plastics, and high-pressure decorative laminates. Figure IV-4 illustrates a typical continuous panel line using steel skins on both faces. It is clear that continuous panel production is a modification of free-rise rigid slab technology.17/

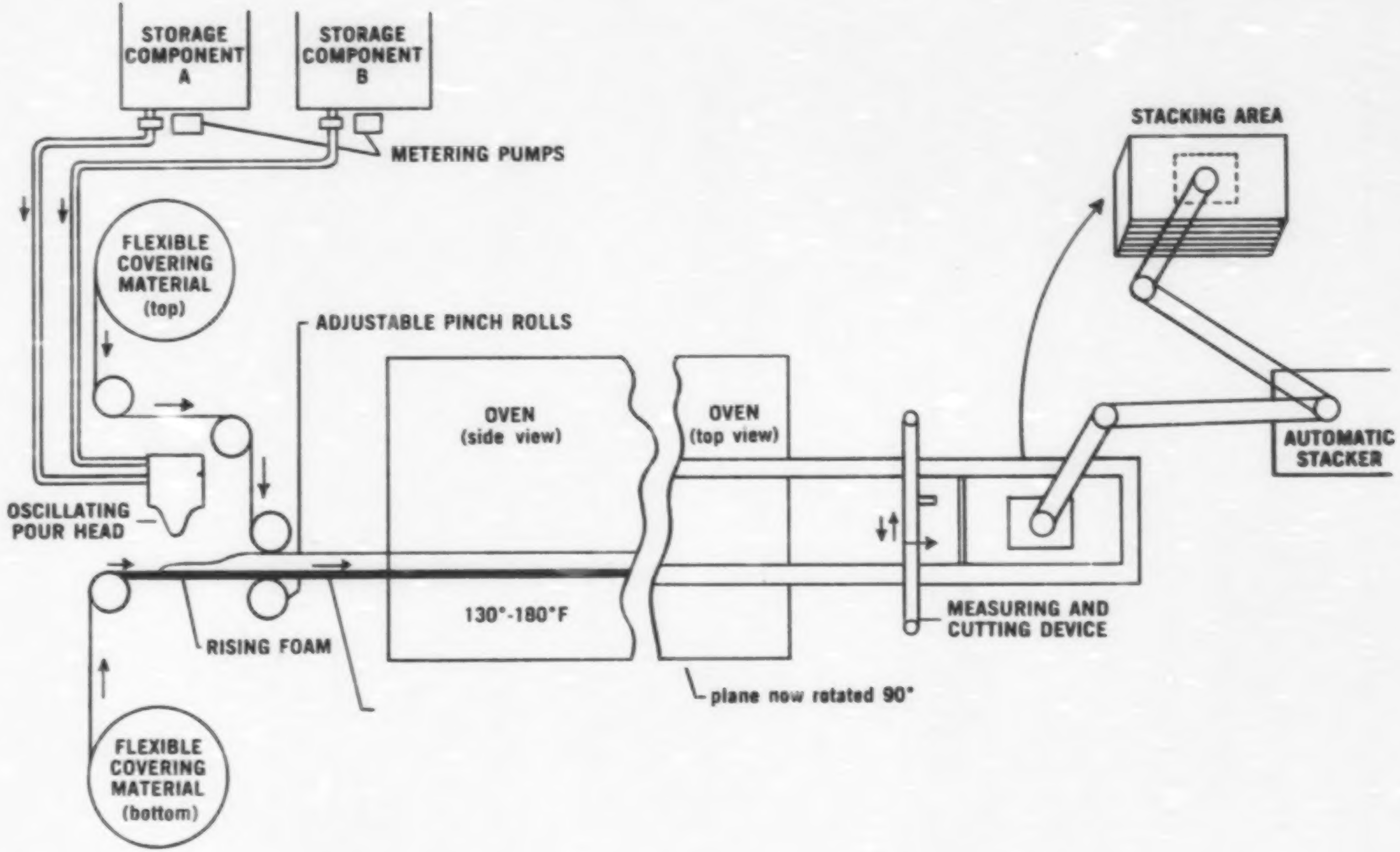
STORAGE COMPONENT A
STORAGE COMPONENT B
METERING PUMPS
STACKING AREA
FLEXIBLE COVERING MATERIAL (top)
ADJUSTABLE PINCH ROLLS
OVEN (side view)
OVEN (top view)
AUTOMATIC STACKER
OSCILLATING POUR HEAD
130°-180°F
MEASURING AND CUTTING DEVICE
RISING FOAM
plane now rotated 90°
FLEXIBLE COVERING MATERIAL (bottom)

Figure IV-4. Sandwich panel production - continuous process

Principal features which differentiate panel production from boardstock are:

- Larger number of producers,
- Smaller output per plant,
- Lower urethane pour rates,
- Reduced chlorofluorocarbon losses in foaming,
- Essentially zero chlorofluorocarbon loss after panel is formed.

There are so many panel fabricators using diverse production processes that no adequate data are available regarding chlorofluorocarbon consumption and losses. The preceding boardstock model plant will be used with the following modifications assumed for a plant manufacturing 425 panels per shift as shown in Table IV-9. With these changes, the chlorofluorocarbon consumption and emissions for the plant can be estimated.

Chlorofluorocarbon Usage and Losses

* Total consumption	1,746 lb/shift
* Losses in materials handling	18 lb/shift
* Loss of chlorofluorocarbon in foaming	26 lb/shift
* Contained in panels	1,702 lb/shift

Rigid Foam-In-Place Cavity Filling

Foaming in place involves pouring the liquid mixture of foam components from the dispensing head directly into a cavity (such as the walls of a refrigerator or boat hull). The chemical reaction causes the blowing agent to expand, and the foam completely fills the cavity. Considerably accuracy and uniformity is required in dispensing the urethane into cavities and molds. Each volume of the liquid urethane deposited expands 30 times in volume and therefore must be accurately measured and precisely placed within the mold or cavity in order to insure accurate filling, and avoid excessive pressure on the sides of the mold or product.

Table IV-9. MODEL FOAM CORE STRUCTURAL PANEL PLANT

1. Panel line operates for 6 hr per 8-hr shift, 240 days/year.

2. Pour rate: 40 lb of urethane system per minute.

3. Panel size: 5 ft x 9 ft x 3.5 in. thick; foam thickness: 3.0 in. x 5 ft wide (1.25 ft^2 cross section).

4. Foam density: 3.0 lb/ft^3; 13.3 ft^3/min.

5. Conveyor speed: 10.6 ft/min; foam tunnel covers first 10 ft; ventilation provided by 5,000 cfm fan.

6. Chlorofluorocarbon content of system: 12% by weight; 4.8 lb/min.

7. Foam yield 98.5% of liquids dispensed; chlorofluorocarbon loss during foam rise accounts for nearly all weight losses, i.e., ~ 1.5% or 0.072 lb/min.

8. Material handling chlorofluorocarbon losses > 1% of consumption.

The froth process introduced in the early 1960's is being used to an increasing degree to minimize these problems. The frothing process involves the addition of another blowing agent, usually fluorocarbon-12 (alternatively, F-114 or F-115 may be used) injected directly into the mixing head. The mixing head operates at a pressure of about 100 psi to keep the frothing agent liquid until it emerges from the dispensing nozzle into the cavity or mold. The reaction and further expansion of the foam roughly doubles the froth volume, thus filling the cavity or mold without excessive pressures, and permitting more accurate filling of cavities.

The frothing pour process has become increasingly important for cavity and mold-filling applications. Refrigerators and freezers represent one of the most important applications of rigid froth pour-in-place foams. Thin-wall refrigerators can use approximately one-half the usual insulation thickness, thus resulting in up to 35% greater interior capacity. The average foam usage is 9 to 12 lb/unit. Froth foam is placed in the cavity between the refrigerator liner and the outer steel shell to bond the two surfaces together and completely fill the cavity.

When nonfrothed resins are used to generate foams of 2 lb/ft^2 density, complex jigs and supports must be used to contain the molds or sheets and prevent distortion during foaming. Pressures developed by foaming in cavities 1 to 2 in. thick may reach 2.5 to 3.8 psi on the walls of the mold, because of the high expansion ratio, and because about 5% excess urethane must be added to insure a complete foam fill.[18]

When froth poured foam is used, the foam expansion exerts only about 0.4 psi on the surrounding walls. Simple, flat walls on building panels or mobile homes and trailers require only minimum supports and jigs--usually plywood support is adequate. Refrigerator doors containing shelves, separators, and egg trays may require more complex jigs and fixtures. The foams have sufficient flowability to fill narrow and complex mold cavities such as thin shelves and egg frame protrusions of a vertically filled refrigerator door, but small holes must be positioned to allow the escape of air during the foaming process. These holes seal themselves as the foam gels.

Because the jigs and support fixtures for foaming to fill a refrigerator shell or the double hull of a pleasure boat often weigh several times as much as the product itself, many cavity filling lines are designed with several clamp and jig stations served by a single foam dispensing head. It is easier to bring refrigerator shells to the fixtures, than to attempt to deliver fixtured cabinets to a stationary foam head.

Factory poured foam and froth for cavity filling applications accounted for the following production volumes in 1975.

Poured and Froth Foamed-In-Place Rigid Urethane, 1975
(millions of pounds)

	Total rigid urethane foam	Foamed-in-place Froth	Foamed-in-place Total
Refrigeration appliances	72.6	40.0	66.8
Insulated housewares, picnic coolers, etc.	11.1	3.3	8.4
Boats and marine flotation	13.8	6.2	12.4
Insulated transport carriers	48.4	23.2	38.7
Automotive and aerospace	9.5	1.5	4.9
Building components and modules	36.5	8.8	29.2
Miscellaneous	8.8	1.4	3.5
Total	200.7	84.4	163.8

Because of the wide acceptance of froth foam cavity filling in deep freezers, refrigerators, boat hulls, and truck trailers, of the indicated 164 million pounds of foam, pre-frothed foam filling accounted for about half of the total foaming-in-place.

Urethane systems for froth pouring as thermal insulation foam suitable for a deep freezer typically contain from 11 to 12.5% F-11 with from 3 to 6.0% F-12 as blowing agents. The maximum F-12 content is 6% by weight; any excess will be lost without aiding the process.

Model Foam-In-Place, Cavity Filling Operations - An appliance cabinet foam insulation line will be used as typifying current practice in cavity foam filling. Similar types of installations are used for boats, truck trailers, and many other foam-in-place applications. The characteristics of a model foam-in-place plant operation is shown in Table IV-10.

The largest refrigerator manufacturers such as Frigidaire, Whirlpool, General Electric, and Westinghouse each consumed about 6 million pounds of urethane systems in 1975. Smaller plants of which Amana, Philco, Gibson, Norge, and Admiral are fairly typical, each generate approximately 1.5 to 2 million pounds at current production levels. Each plant may have several cabinet insulation filling lines.

Table IV-10. MODEL FOAM-IN-PLACE, CAVITY FILLING PLANT (FREEZER INSULATION LINE)

1. Plant produces 4% of U.S. freezer output for 1975, i.e., 2,457,000 freezers x 0.04 = 98,300 units.

2. Plant operates 250 days/year; one 8-hr shift per day; daily output - 393 freezer units, ~ 49 units/hr.

3. Freezer sizes range from 14 ft^3 (26% of output), up to 22 ft^3 (34% of output). Average foam insulation requirement for all models, 17.2 lb/unit.

4. Foam requirement - 1.691 million pounds per year; 6,763 lb/day.

5. Cycle to jig cabinets and doors in fixtures, froth-fill, cure foam and remove from fixtures ~ 20 min. Each support fixture is used three times per hour.

6. Insulation is applied on three foam lines, all served from one urethane system preparation unit. Two cabinet lines, each have eight sets of fixtures. One door line uses 16 support fixtures. Total throughput averages 48-50 insulated units per hour. Ventilation for the three filling stations provided by common ductwork with 10,000 scfm fan.

7. Urethane system contains 12.0% F-11, plus 4.5% F-12. Each cabinet requires an average of 10.2 ft^3 of foam at 1.7 lb/ft^3 density. Total chlorofluorocarbon use in foam is 278,975 lb/year.

8. Chlorofluorocarbon vapors emitted from froth filling: 10% of F-11 dispensed (0.206 lb/unit); 35% of F-12 dispensed (0.271 lb/unit); chlorofluorocarbon vapors - 0.477 lb/unit, total 46,919 lb/year.

9. Chlorofluorocarbon losses in mixing, handling, and transfer - 1.2% of consumption in foam ~ 3,348 lb/year.

On-Site Application of Rigid Urethane Foams

Rigid insulating urethane foams are applied on the job site by a large number of contractors, as well as by industrial plants and transportation firms. The major uses include building construction, insulation of industrial tanks, foam coating of railway freight and tank cars, roofing and the construction of thermally insulated pipelines. These foams are nearly always applied by foam spraying, although a small volume of froth-poured wall cavities are filled on-site. An increasing number of petroleum pipelines are being insulated in the field, either using portable foam application machines, or by pouring foam into an annular shield around the pipeline as it rests "over-the-trench." Large ship insulation and barge flotation jobs represent a slightly different category because of the very high volumes involved, and the high rates of pour required.

There are currently some 200 foam contractors with 176 firms forming the membership of the Urethane Foam Contractors Association.19/ In addition, information compiled by the UFCA shows that more than 650 firms currently own foam spray application equipment, and purchase urethane foam systems of the class used for job site foaming.

There are no industry estimates of the total poundage of urethane foams applied on-site. It is not likely that 1975 consumption would exceed the following estimates:

On-Site Foam Insulation, 1975
(millions of pounds)

	Total rigid urethane	On-site application
Building construction and roofing	133	16
Transport carriers	36	9
Industrial tank and pipe	44	14
Marine and flotation	10-13	4
Miscellaneous	8-15	3
Total	266	46

The urethane systems employed for sprayed-on foams are extremely reactive, so that a gelling polymer structure is produced almost immediately on leaving the spray head. A gel time of 6 to 12 sec is fairly typical for sprayed walls or roof decks. Chlorofluorocarbon content ranges from 8 to 12% for sprayed foams, and up to 10 or 12% for the minor quantity of froth sprayed and poured foams.

Application contractors report that the foams set so rapidly that there is no visible evidence of foam bubbles rupturing as the foam expands on the surface. Because the atomized system is broken up to expose a large surface area for the fraction of a second between the run and the surface, some chlorofluorocarbon evaporation is to be expected. The consensus of two application contractors[20] and two equipment suppliers[21] is that no more than 10% of the blowing agent used escapes to the atmosphere. These estimates specifically include all overspray losses in application. (Spraying overhead on ceilings can result in up to 15% weight loss; vertical surfaces and roof tops average 96% foam yields if sprayed when wind is not a problem.) There is essentially no on-site loss of chlorofluorocarbons due to handling and preparation of the mixed system because virtually all applicators purchase prepared systems in tanks or drums, ready for field spraying. Losses by large suppliers probably average less than 0.5% of the chlorofluorocarbon content.

Because low volatility isocyanates are employed, there are no reported problems with toxic vapors, and special ventilation is not normally provided for jobs where foams are applied in unconfined work places. A few contractors have attempted to use plastic tents or inflatable enclosures to permit spraying under less favorable wind conditions (for example, the New Orleans Super Dome). However, the use of enclosures is not at all common.

Estimation of Chlorofluorocarbon Losses - Due to the extreme diversity of on-site foaming, the emissions from the entire sector will be estimated rather than attempting to define a model plant. The maximum emissions of chlorofluorocarbons from on-site rigid urethane foams (both sprayed and frothed) is estimated as follows:

Total:	46 million pounds of foams
	40 million pounds sprayed at 12% F-11
	6 million pounds frothed at 10% F-11 plus 4% F-12

Chlorofluorocarbon losses:

F-11	540,000 lb/year
F-12	48,000 lb/year
Total	588,000 lb/year

SUMMARY OF CHLOROFLUOROCARBON CONSUMPTION AND EMISSIONS

The foregoing discussion of chlorofluorocarbon usage and processing losses may be summarized by comparing the quantities consumed in the six basic processes. Two summary tables are provided for this purpose. Table IV-11 compares the annual foam output for each model plant (except on-site foams which are for the entire industry sector), showing total usage, and emissions at various stages of production and processing. All chlorofluorocarbons used in making flexible foams is emitted to the atmosphere fairly promptly. The great preponderance of chlorofluorocarbons trapped in rigid foams will be retained for many years. Perhaps two-thirds of the quantity initially found in 24-hr-old rigid urethane foams will be retained for the useful life of these foams.[22/] On final destruction of the building, deep-freeze or other insulated product, the entrapped chlorofluorocarbons will be released. At least for a number of years into the future, chlorofluorocarbons consumed in insulating foams represent a storage depot, contributing only minor amounts of atmospheric emissions.

The second summary, Table IV-12, presents a reconciliation of total chlorofluorocarbon losses from each type of foam process. By using estimates of 1975 output of each foam and the fraction of this production blown with chlorofluorocarbons, the equivalent number of model plants required can be derived. For example, the indicated 32 to 38 flexible slab lines using chlorofluorocarbon blowing agents is of the right magnitude. About 25 producers or plants running continuous foam machines can be identified. There doubtless are others, and some plants operate more than one foam line, but some 30 to 40 plants of the size specified appear to be realistic.

Total indicated chlorofluorocarbon emissions for 1975 are given in the last column of Table IV-12. The 30 to 40 million pounds from flexible foams is slightly lower than the estimate of 35.4 million pounds for 1973 prepared by A. D. Little.[23/] One reason for part of the decline has been the increasing use of methylene chloride as an auxiliary blowing agent for less critical types of flexible urethane foams. Thus, only some 33% of flexible foams were blown with chlorofluorocarbon agents in 1975 versus nearly 42% in 1973. The present estimate of emissions from rigid foams totaling 6.8 to 8.5 million pounds in 1975 is also lower than the 9.0 million pounds indicated by A. D. Little. Here the difference arises from our use of slightly lower estimates of losses in foam production.

The general agreement of these independent estimates suggests that the allocations of emissions by stage of processing, as given by Table IV-11, form a sound basis for giving preliminary consideration to the technical feasibility of recovering chlorofluorocarbons from foams.

Table IV-11. CHLOROFLUOROCARBON CONSUMPTION AND EMISSIONS, URETHANE FOAMS

Type of foam, process (model plants, see text)	Foam output of plant (million lb/yr)	Total FC consumption (lb/yr)	Mixing and handling loss (lb/yr)	Foaming loss (lb/yr)	Processing loss - 1 (lb/yr)[a]	Processing loss - 2 (lb/yr)[b]	Processing loss - 3 (lb/yr)[c]	FC retained in product (lb/yr)	Total FC emissions (lb/yr)
Flexible, continuous bun or slab	8.17	846,612	4,212	421,200	168,480	84,240	151,632	16,848[d]	846,612
Flexible, molded shapes	2.22	183,418	8,611	17,222 +8,611[e]	43,056	68,890	25,843	8,611[d]	183,418
Rigid, continuous boardstock	9.43	1,527,120	15,120	216,000	-	-	60,480	1,235,500	291,600
Structural, foam core panels	3.40	418,847	4,147	51,840	-	-	-	362,880	55,987
Foam-in-place, cavity filling	1.69	282,323	3,348	46,919	-	-	-	232,056	50,267
Rigid foams, applied on-site (entire industry segment)[f]	46.00	5,640,000	-	588,000	-	-	-	5,052,000	588,000

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[a] Processing losses are (1) secondary conveyors.
[b] Processing losses are (2) bun cut-off station and conveyor.
[c] Processing losses are (3) aging and cutting to finished sizes.
[d] Chlorofluorocarbon remaining in flexible foams at shipment diffuse to atmosphere within 30 days.
[e] Lead and lag chlorofluorocarbon flush of mixing head.
[f] Total on-site application sector for U.S.; not directly comparable with preceding model plant figures.

Table IV-12. ESTIMATION OF CHLOROFLUOROCARBON EMISSIONS FROM URETHANE FOAMS - 1975

Type of foam, process	U.S. output (million lb)	Percent FC blown	FC blown (million lb)	Model plant output (million lb)	Total FC emissions plant (lb/yr)	Number of plants required	Indicated total U.S. emissions FC (million lb/yr)
Total U.S. flexible urethane	924[a]-1,044[b]						
Flexible, continuous bun or slab	660[a]-775[b]	33	218-256	8.17	846,612	27-31	22.8-26.2
Flexible, molded shapes	264[a]-269[b]	30	79-82	2.22	183,418	36-38	7.0-7.3
Total, flexible							29.8-33.5
Total U.S. rigid urethane	340[b]-383[a]						
(Total rigid, except furniture)	320[b]-348[a]						
Rigid, continuous boardstock	96[d]-127[c]	95	91-121	9.43	291,600	10-13	2.9-3.8
Structural foam core panels	42[d]-57[c]	90	38-51	3.40	55,987	11-15	0.6-0.8
Foam-in-place, cavity filling	106[d]-128[c]	85	90-109	1.69	50,267	53-65	2.7-3.3
Rigid foams, applied on-site (Entire industry segment)[f]	36[d]-48[c]	95	34-46	46.00[e]	588,000[e]	500-600[e]	0.6
Total, rigid							6.8-8.5
Totals, all urethanes							36.6-42.0

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[a] Based on Modern Plastics, Reference 1.
[b] Based on Mobay survey, Reference 2.
[c] Estimated using Modern Plastics, see Table IV-8.
[d] Estimated using Mobay survey, see Table IV-8.
[e] Total on-site applied foam, not strictly comparable with model plants above.

POLYSTYRENE AND POLYOLEFIN FOAMS

Use of chlorofluorocarbon blowing agents in other foams is significant only for three types of plastics:

- * Polystyrene sheet and film (extruded),
- * Polyolefin medium density flexible foams, and
- * Polystyrene boardstock made for thermal insulation.

Foamed polystyrene sheet and films are extruded from high molecular weight "crystal" resins for products such as egg cartons, disposable serviceware, cushioning sheets, and packaging products. Typically the blowing agent is iso-pentane, or a mixture of pentanes with chlorofluorocarbons 11 and 12. Total blowing agent ranges from 5% to as high as 8% of the extrusion mixture. In 1975 some 539 million pounds of extruded foam sheet was produced. Consumption of chlorofluorocarbon blowing agent was not reported, but may be estimated at less than 7 million pounds. Blowing agent vapors diffuse fairly readily out of the thin and flexible foamed sheet. None of the producers contacted had attempted recovery of blowing agents. Because the sheet is extruded from ring die, pulled over a sizing and cooling mandrel, then slit and wound into rolls, there is little time or opportunity to collect vapor emissions at the extruder. The possibility of recovery from the wound rolls has not been explored so far as could be learned.

Styrofoam extruded boardstock for thermal insulation is produced in the U.S. exclusively by Dow Chemical Company. Patented mixtures of methyl chloride and chlorofluorocarbons are employed as blowing agents. It is essential that the halogenated vapors be retained within the foam to provide a low thermal conductivity. Therefore the vapor concentrations at the point of production are quite low (well below 1,000 ppm at all times and locations).34/

Consideration has been given by Dow to vapor recovery. Carbon adsorption, compression-condensation, and use of the relatively new "imbiber beads" (developed for collecting organic spills) have been evaluated. At present none of these approaches are considered technically feasible for low vapor concentrations. All of the recovery techniques considered are judged to be impractical for economic reasons as well. Chlorofluorocarbon consumption for styrene board is estimated to be less than 0.5 million pounds, with emissions probably less than 0.1 million pounds per year.

Roughly 20 million board feet of polyolefin foams were blown in 1975 for packaging, impact cushioning and flotation uses. Chlorofluorocarbons F-12 and F-11 are most widely used as blowing agents for thin packaging foams. Dow's ethafoam, made in higher densities and heavier cross sections, is often foamed with F-114.[34] Densities range from 1.5 to 5.0 lb/ft^3. For an average density of 3.5 pcf, total use of chlorofluorocarbon agents would be less than 0.6 million pounds for 1975.

Thus these three types of plastic foams together represent possibly 15% of the chlorofluorocarbon agent emissions from foams. No vapor recovery methods are now used. Polystyrene film and sheet extruded from crystal resin is the only type of operation that might lend itself to vapor collection and control. However, there is currently no information on which to predict either the technical feasibility of recovery, or the potential costs involved.

CONTROL SYSTEMS FOR CHLOROFLUOROCARBON EMISSIONS

The basic technology available for control of solvent vapor emissions to the air, and the design of equipment to achieve the desired reductions in emissions have been described in detail.[24-27] Only those features of chlorofluorocarbon vapor control which influence either the performance or the cost of emission control systems will be considered.

Among the emission control systems that have been proposed for reducing chlorofluorocarbon emissions in plastic foam production are:

- Adsorption with solvent recovery,
- Incineration (with heat recovery),
  - (a) Direct flame pyrolysis,
  - (b) Catalytic incineration,
- Absorption (scrubbing) with recovery, and
- Vapor condensation and recovery.

Systems Not Applicable for Blowing Agent Vapors

Preliminary analysis indicates that neither refrigeration condensation, nor absorption by scrubbing are technically feasible for recovering relatively low concentrations of chlorofluorocarbon vapors from high volume air streams. The rationale for dropping these approaches from further consideration are summarized briefly.

Vapor Condensation - Use of refrigeration for direct condensation of solvent vapors from exhaust air streams has been proposed, and even tested on a limited basis as a means of recovering solvents. To date, no successful operations have been reported.

Any component of a vapor mixture can be condensed if brought to equilibrium at a low enough temperature. The temperature necessary to achieve a given solvent vapor concentration is dependent on the vapor pressures of the compounds.

When cooling a two-component vapor where one component can be considered noncondensible, for example, a solvent-air mixture, condensation will begin when a temperature is reached such that the vapor pressure of the volatile component is equal to its partial pressure. As the vapor is cooled further, condensation continues such that the partial pressure stays equal to the vapor pressure. The more volatile a compound, i.e., the lower the normal boiling point, the higher will be the amount that can remain vapor at a given temperature. The higher the concentration of a component in the vapor, the greater the percent condensed will be at a given temperature.

Concentrations of chlorofluorocarbon vapors in exhaust air from most foam production plants may occasionally reach 2,000 ppm or higher; concentrations of 200 to 500 ppm are more common.

To condense 90% of F-11 from an air stream containing initially 2,000 ppm F-11, a temperature well below -120°F (-84.5°C) (partial pressure of 0.00735 psi) is required.[28/] The usual thermophysical property tables seldom offer values below this range.

At these temperatures, ice formation reduces condenser effectiveness rapidly, and the problem of removing the condensed mist of solvent droplets from the moving air stream is difficult. The cost of refrigeration equipment and excessive energy consumption (even with the most efficient exchangers for recovery), prohibit any practical application of direct condensation as a means of recovering chlorofluorocarbons from dilute air streams of high volumetric flow rates.

Absorption - Liquid absorption is a well-known process for removing contaminants from air streams. This process typically employs a packed column to provide contact between the absorbing fluid and the gas stream. It has been proposed that chlorofluorocarbon vapors could be scrubbed out of exhaust air using mineral oil as the absorbant. Because the chlorofluorocarbon vapor is relatively dilute in the exhaust air, large size columns would be required. A limiting condition usually is the quantity of absorbant vapor exiting with the air from the stripping column.

For petroleum based oils (100 SSU refined mineral oil) the air stream from a scrubber at 100°F (38°C) would contain more than 100 ppm of oil vapor (plus any entrained mist). This would partly alleviate one air pollution problem, only to replace it with another. Additionally, progressive oxidation of mineral oils would contribute a significant odor problem, since blown oils and waxes are among the most characteristic and offensive odorous compounds at extremely low concentrations.

Special vacuum distilled and carefully refined oils are available that have exceedingly low vapor pressures. Alternatively, esters of low vapor pressure such as di-octyl phthalate and other nonvolatile plasticizers might be used. The high cost of such absorbants (> $15/gal) weighs against their use in such a large-scale process.

No experimental data have been reported to suggest that liquid absorption can be successfully used to remove chlorofluorocarbons at low concentrations from high volume exhaust air streams.

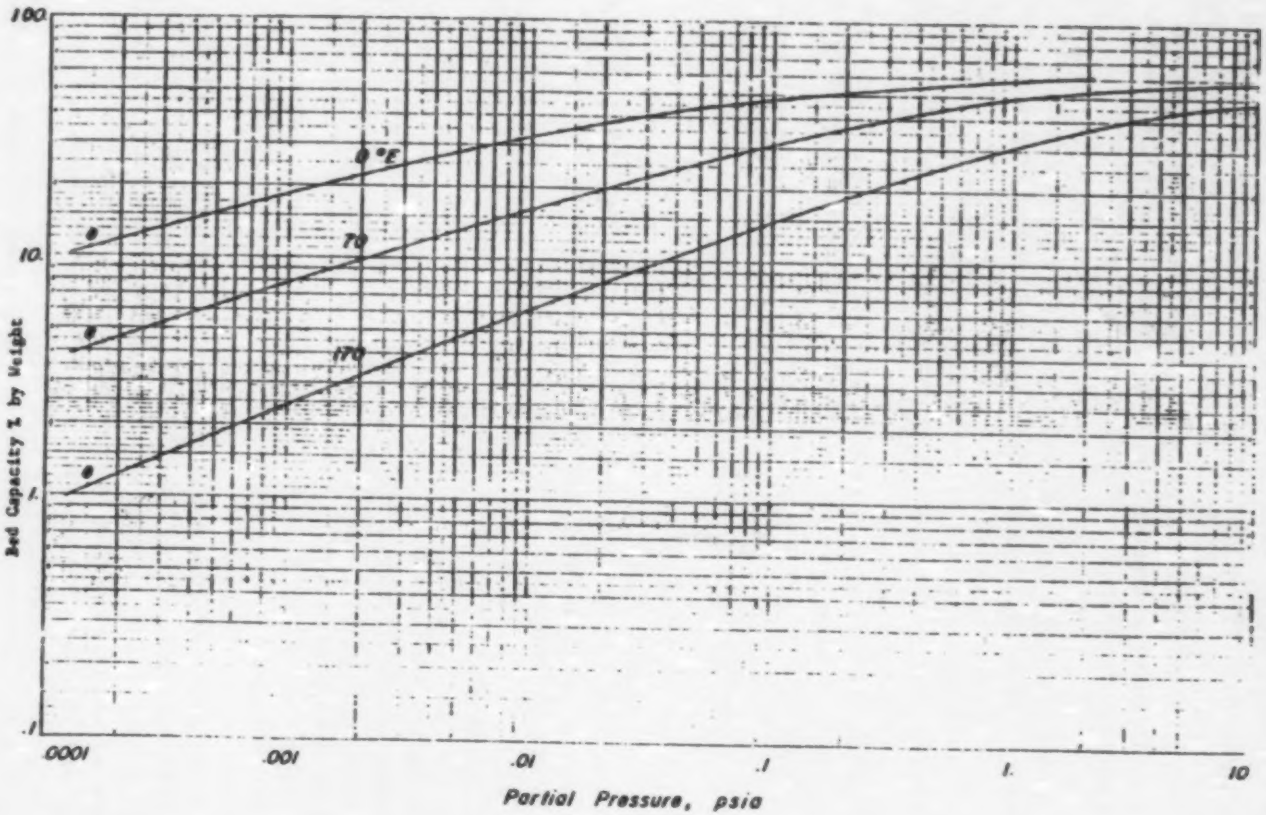
Systems not Economical for Low Concentrations

Most evaluations reported in the literature[24,26,29,30] show that incineration, either direct flame or catalytic combustion, is more costly than adsorption systems for low vapor concentrations. Even with 60% heat recovery, the cost of incineration systems does not appear favorable when compared with recovery systems.

Carbon Adsorption Systems

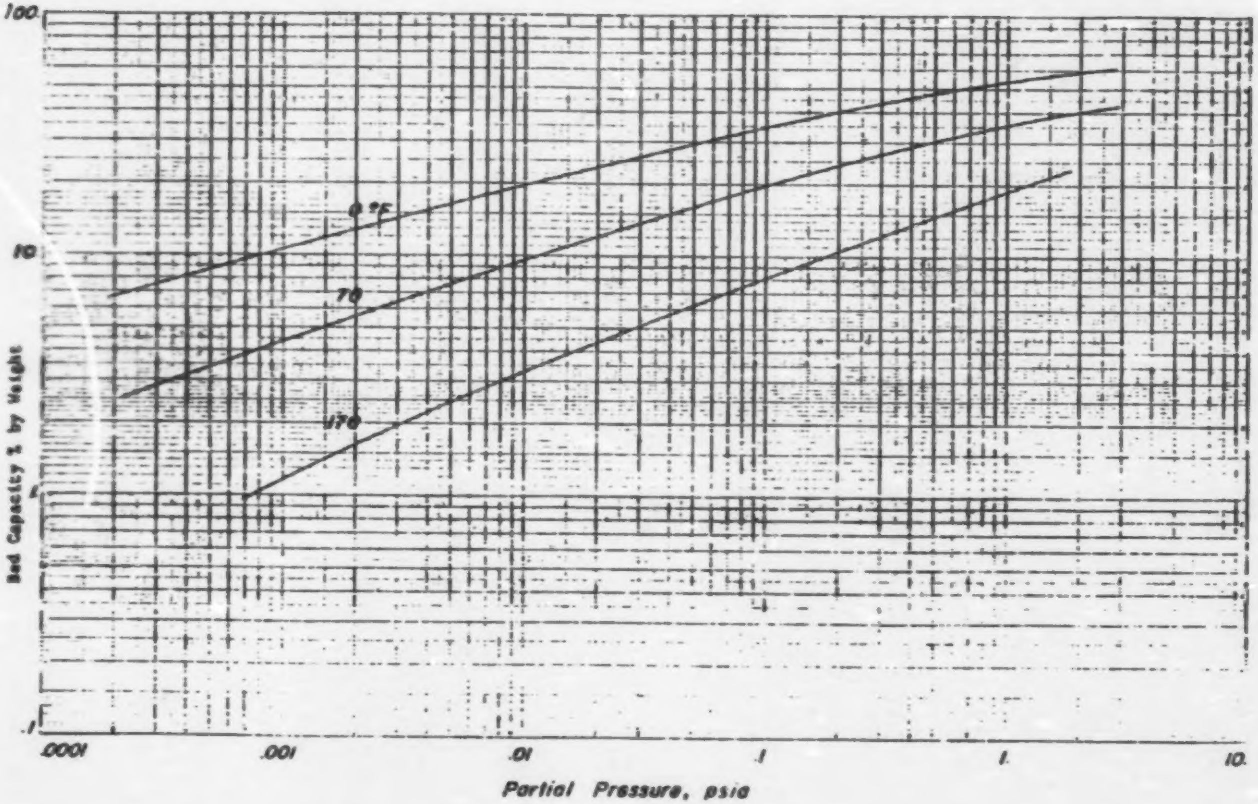
Activated carbon adsorption has been used commercially for solvent recovery for many years. If chlorofluorocarbon vapors are to be concentrated and recovered from the relatively lean exhaust air streams typical from plastic foam production, systems using carbon adsorption must be considered. The theory, design, and performance of carbon adsorption systems has been thoroughly covered,[24,25] and will not be repeated here.

An extensive survey of foam producers, carbon adsorption system purveyors, chlorofluorocarbon manufacturers, and foam equipment firms, has failed to find a single instance in which a carbon adsorption system (or any other class of emission controls) has been tried or evaluated for the collection and recovery of chlorofluorocarbons from plastic foam production. Smaller, but basically similar adsorption units have been successfully used for the recovery of F-113 solvents used in vapor degreasing. Basic adsorption isotherms for F-11 and F-12 have been determined (see Figures IV-5 and IV-6), along with practical bed capacity data and other information required to design both adsorbers and regeneration



Source: Activated Carbon Division, Calgon Corporation

Figure IV-5. FC-11 adsorption on BPL activated carbon



Source: Activated Carbon Division, Calgon Corporation

Figure IV-6. FC-12 adsorption on BPL activated carbon

sections. In short, there is no known reason why carbon adsorption cannot be successfully applied to recovery of foam blowing chlorofluorocarbons. A few problems are encountered which may influence performance, maintenance, and initial cost and operating expenses for such systems.

In order of importance, the factors that must be considered in applying this proven technology to the reclamation of chlorofluorocarbons from foam production are:

1. Reducing the volume (flow rate) of air to be treated.

2. Pretreatment of the air stream to remove contaminants.

3. Design of an efficient regeneration/condensation unit.

4. Possible corrosion problems due to halogens.

5. Maintaining uniformity and quality of reclaimed chlorofluorocarbons.

Reduction of Air Flow - The importance of minimizing the volume of air in which the chlorofluorocarbon vapors are transported to the adsorption beds cannot be over emphasized. More than any other factor, the air flow rate determines the capital cost of adsorption systems. Air volume also strongly influences the quality of performance, ease of automatic control, and the annual cost of operation. The total economics of recovery is so sensitive to air flow, that it is difficult to make meaningful comparisons against possible alternatives until the practical limits of vapor collection trade-offs are reasonably well defined.

Removal of Contaminants - For those foams that utilize the more volatile isocyanates such as TDI (i.e., chiefly flexible slab and molded urethanes), up to 1 ppm or more of isocyanate vapor may be found in the air exhaust from the foam dispensing area. Isocyanate vapors react fairly rapidly with moisture in the air stream to form particles that can be filtered out of the air stream. However, any isocyanate residues reaching an activated sorption bed would be strongly bound, gradually reducing bed capacity for the chlorofluorocarbons. A small quantity of steam injected into the collection hood or duct, has been suggested as one means of removing unwanted isocyanate vapors.[31] Since the efficacy of this approach is not yet known, it may be necessary to employ water sprays or wetted fiber filters to insure removal of amines, isocyanates, surfactants, or any entrained polyols. If this type of pre-treatment of the air stream is required, the extra cost of the contaminant removal section must be added to any basic emission control system. Injection of small quantities of steam should not appreciably increase costs. If steam addition and filtration removes the contaminants, the customary filter used to protect the sorption beds should suffice.

Regeneration of Adsorbent - Low pressure steam regeneration of the adsorbent beds is customary. For recovery of low boiling chlorofluorocarbons, there are certain special requirements which complicate the design of an efficient regeneration/condensation cycle.

After steam regeneration, the carbon bed is wet. To maximize the adsorbent capacity for chlorofluorocarbons, partial drying of the bed is desirable before switching back from steam regeneration to vapor recovery. This can be accomplished by passing hot air through the bed for a few minutes, or by using chilled heat exchanger coils ahead of the beds to reduce humidity in the vapor passed through the carbon beds. This feature can be omitted, but the bed capacity will be adversely affected. It is customary to pass dry air through the steamed out carbon for 15 to 20 min after regeneration. An alternative procedure is to regenerate the beds using heated air rather than steam.

There is little or no problem in condensing and recovering F-11 vapor (boiling point 75°F or 24°C) displaced during steam or air regeneration. If recovery of F-12 is required, a two-stage condenser section may be needed. Water vapor and F-11 would be condensed at 33 to 40°F (2 to 5°C), and the F-12 (boiling point 23°F or -0.5°C) condenser would operate over the range of +30° to -20°F (-0.1 to -29°C). For foams utilizing only minor quantities of F-12, it may be too expensive to attempt recovery of the low boiling chlorofluorocarbon.

Corrosion and Materials - The chlorofluorocarbons do not hydrolyze easily, and potential corrosion problems are less severe than are regularly encountered in vapor recovery systems used for ordinary chlorinated hydrocarbons. Galvanized steel, aluminum and other reactive metals are not satisfactory for ducts and hoods. The common plastic or reinforced plastic ventilation and fume ductwork is preferred. Adsorbent tanks can be made of phenolic lined carbon steel, or nickel base alloys such as monel. Low alloy stainless steels of the 300 series are, however, not satisfactory.[32]

Quality and Uniformity of Recovered Solvent - For a single chlorofluorocarbon, such as F-11, no difficulties are anticipated in recovery; however, it is customary to decant the solvent through a drying filter to remove the trace of dissolved water remaining.

If methylene chloride, etc., is employed as a cleanup solvent, its vapors may be recovered along with the chlorofluorocarbon. Providing that the proportion of methylene chloride is less than about 5 to 10%, there should be no problem in reuse of the solvents as blowing agents for flexible foams.[33] If the quantity of wash solvent is sufficient to cause problems in foaming, it may be necessary to close the recovery system during flushing and cleanup.

In certain cases where methylene chloride and F-11 are used together, a significant amount of the more soluble methylene chloride is lost into the water phase of the condenser tank. This change of proportion may be sufficient to require that the recovered solvent be analyzed and brought back to the specified mixture before reuse.

Feasibility of Chlorofluorocarbon Recovery - The technology of activated carbon adsorption appears to be suited for the recovery of chlorofluorocarbon vapors from foam production. In the absence of any reported attempt to apply solvent recovery to commercial foam processes, the practicality of collecting and recovering chlorofluorocarbon emissions from the model plants previously defined was considered.

The engineering limitations of greatest importance are:

1. The effectiveness with which chlorofluorocarbon emissions from foam can be picked up by hoods, enclosures and ventilating systems that could be provided at various stages of processing.

2. The lowest air flow rate that will provide both effective chlorofluorocarbon vapor collection, and maintain safe levels of toxic vapors in the workspace near the foam equipment.

3. The concentration levels of blowing agent in the exhaust air resulting from considerations (1) and (2) above.

For each stage of foam manufacture as specified for the model plants, the volumes of chlorofluorocarbon vapors, and the typical ventilation rates were used to compute the concentrations that would result if all of the vapors were directed into the air exhaust. This assumption can then be relaxed to approximate the best attainable commercial practice. Table IV-13 presents values for both the quantities of chlorofluorocarbon to be recovered, and the maximum concentrations in parts per million for five types of foam processes. Obviously, the indicated concentration levels would increase if the chlorofluorocarbon vapors could be collected using smaller blowers.

Table IV-13. MAXIMUM AMOUNTS AND CONCENTRATIONS OF CHLOROFLUOROCARBON (Based upon model plant conditions)[a]

Foam process	Source of chlorofluorocarbon (FC)	lb FC/min	cu ft FC/min[b]	Air (cfm)	FC conc. (ppm)
A. Flexible slab	Foam tunnel	18.0	53.4	20,000	2,672
	Conveyor	7.2	21.4	10,000	2,140
	Cut-off take-out	3.6	10.7	15,000	714
	Aging room	6.5	19.3	20,000	963
	Total	36.0	107.0	65,000	avg 1,647
B. Molded parts	Pour mold	0.156	0.464	10,000	46
	Rise and cure	0.078	0.232	None	-
	Demolding	0.390	1.159	5,000	232
	Postcure	0.624	1.855	5,000	371
	Crush, flex	0.234	0.696	None	-
C. Rigid boardstock	Foam tunnel	7.78	23.12	5,000	4,625
	Trim and slab saw	2.78	8.26	dust only	(1,652 for 5,000 cfm)
D. Structural foam panels	Foam conveyor	0.60	1.78	5,000	357
E. Cavity-foam-in-place	Foam fill station	0.39	1.16	10,000	116

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[a] No values given for on-site foaming; ventilation systems not employed.

[b] Volume of vapors at 100°F, temperature of air ducts.

The values shown in Table IV-13 suggest several observations. The quantity of blowing agent vapors available for recovery is by far greater in a flexible foam slab plant than any other type of process. While the amounts of chlorofluorocarbons are smaller, the potential for vapor recovery from continuous rigid boardstock is also fairly attractive. For flexible molded parts, foam core panels and foam-in-place cavity filling, the prospects for vapor recovery are not as attractive. It might, however, be desirable to consider attempting recovery of vapors released on sawing and trimming rigid stock. The concentration of chlorofluorocarbon vapors, for both flexible and rigid foam machines, lies in a range highly suitable for activated carbon adsorption as a means of recovery. If it were possible to collect a substantial fraction of the chlorofluorocarbon vapors in a smaller stream of air, the costs of recovery would be reduced significantly.

The concentrations and quantities of vapors shown in Table IV-13 are for total collection. At present, of course, much less than all of the vapors are collected along with toxic materials. Even given the best possible enclosures and ventilation systems, it is optimistic to expect collection of more than 70 to 80% of the vapors from any particular stage of processing. The challenge will be to achieve adequate collection with the lowest practical air flow rates. While some improvements can doubtless be made, the extent to which more efficient collection systems can be developed is not known at the present time.

Given proper engineering of chlorofluorocarbon vapor collection systems of satisfactory performance, how much solvent could be recovered? If recovery systems were applied primarily to the more obvious sources of emissions, by how much could total emissions be reduced? These questions will be explored using the figures developed in Table IV-13.

It seems conservative to assume that improved hoods and enclosures (perhaps using ducts drawing from below the foam levels), could achieve minimum levels of collection as follows:

Flexible slabs

Foam tunnel	75 to 85%
Conveyors	60 to 75%
Cut-off, take-out	60 to 75%
Aging room	50 to 65%

Molded flexible	
Mold charge	60 to 75%
Post-cure, crush	70 to 80%
Rigid boardstock	
Foam tunnel	70 to 80%
Trim and slab saw	50 to 65%
Structural foam core panels	
Foam tunnel	60 to 75%
Foam-in-place cavity filling	
Fill station	70 to 85%

Modern carbon adsorption vapor recovery systems are capable of recovering 93 to 98% of all chlorofluorocarbons entering the sorption beds. If the preceding schedule of fractional vapor collection was treated at an average recovery of 95%, the results would be those shown in Table IV-14.

Recovery of chlorofluorocarbons for re-use in foaming may provide attractive cost savings for flexible bun and molded foam producers. From 50 to 70% of the total chlorofluorocarbon requirements might be met by efficient vapor recovery. Recovered blowing agent as a fraction of total consumption is much smaller for all the rigid urethanes. It is unlikely that cost savings alone would induce concern for chlorofluorocarbon emission controls for most rigid foam production.

Economic Evaluation of Chlorofluorocarbon Recovery - Given the present uncertainty relating to chlorofluorocarbon emission rates, and the levels of vapor collection that could be achieved in practice, only a crude and preliminary treatment of expected system costs and potential savings from recovery is warranted.

To indicate the possible range of costs and savings that might be expected, two situations were examined:

1. Recovery of chlorofluorocarbon vapors from the primary foam section of a flexible slab machine.

Table IV-14. POTENTIAL CONTROL OF CHLOROFLUOROCARBON EMISSIONS FROM FOAMS

Foam process and stage	Annual emissions (lb)	% Treated	Annual recovery (95%)	Percent emission reduction	$ Recovered FC; % of consumption
A. **Flexible urethane slabstock**					
Foam tunnel	421,200	85	340,119	80.8	
Conveyors	168,480	75	120,042	71.3	
Cut-off, take out	84,240	75	60,021	71.3	
Aging room	151,632	65	93,633	61.8	
Total plant emissions[a]	846,612	-	613,815	72.5	$245,526 72.5%
B. **Molded flexible parts**					
Molded charge	25,833	75	18,406	71.3	
Postcure, crush	94,724	80	71,990	76.0	
Total plant emissions[a]	183,418	-	90,396	49.3	$36,155 49.3%
C. **Rigid boardstock**					
Foam section	216,000	80	164,160	76.0	
Trim, slab saw	60,480	65	37,346	61.8	
Total plant emissions[a]	291,600	-	201,506	69.1	$80,602 14.8%
D. **Structural foam panels**					
Foam section	51,840	75	36,936	71.3	
Total plant emissions[a]	55,987	-	36,936	66.0	$14,775 8.8%
E. **Foam-in-place cavity fill**					
Filling station	46,919	85	37,887	80.1	
Total plant emissions[a]	50,276	-	37,887	75.4	$15,155 13.4%

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[a] Total plant emissions include all handling and other chlorofluorocarbon (FC) losses, plus FC retained in flexible foams.

2. Recovery of chlorofluorocarbon vapors from the post-cure and crush stage of molded flexible foam parts.

The first recovery system will be custom designed and built to handle relatively large quantities of chlorofluorocarbon in a stream of 20,000 cfm. An equipment allowance of 10% is included to steam remove undesirable isocyanates before entering the carbon beds.

The requirements for the second system are sufficiently small that a pre-packaged, fully automatic solvent recovery system may be chosen. For lower air flow rates, these units do not require attention by an operator, and only regularly scheduled maintenance is typical.

The conventions used in estimating costs and savings are the same for each system, and generous allowances for escalation of equipment costs were included as a hedge against uncertainty:

Equipment life = 15 years,

Interest (discount) rate = 10%,

Capital recovery factor = 0.13147,

Carbon replacement in year 8,

Chlorofluorocarbon price 36¢/lb; 40,000 lb tank truck, FOB delivered,*

Package unit price from VIC Manufacturing Company as of December 1975, and

Custom system price, highest estimate obtained.**

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* F-11 price quoted by E. I. du Pont, Freon Division, per Kevin Coile.

** Prices suggested for carbon adsorption systems ranged from $7 to $15/scfm of air stream. Prices of $7.00, $7.50, $8.00 to $10,00 and $10.00/scfm were for equipment only. Prices of $11.50 (large size) and $15.00 (smaller units) per scfm were for complete turnkey installations and included all controls, and an engineering fee of $4.50/scfm. Price estimates were furnished by: Hoyt Manufacturing Company, Sutcliffe-Speakman Limited, Vulcan-Cincinnati, Calgon Corporation, VIC Manufacturing Company, and Strauss Systems, Inc.

Table IV-15 shows the calculation of annual costs and savings for primary foam section of the flexible foam machine. Given effective (85%) collection of the chlorofluorocarbon vapors, the annual savings from F-11 recovery considerably exceed the annualized costs. This would remain the case, even if less than 50% of the F-11 vapors were collected for recovery.

The economics of recovering the vapors diffusing from molded parts during post-cure and roll crushing are somewhat less favorable. Table IV-16 shows that recovery of nearly 72,000 lb of chlorofluorocarbon yearly will return the capital investment in about 2.5 years. The ratio of annual savings to annualized costs would remain above the break-even point at any vapor collection level above 55%.

The economic projections used are admittedly qualitative and based upon uncertain technical factors. It does appear, however, that collection and recovery of chlorofluorocarbons may be economically feasible for those locations where substantial quantities of vapors can be collected. The actual determination of these locations is essential to further consideration. Analytical studies are needed, together with investigations of the performance of modified ventilation systems.

Table IV-15. CALCULATED SAVINGS/COST RATIO FOR CHLOROFLUOROCARBON RECOVERY

Basis: Foam tunnel of flexible urethane slab model plant

Air flow rate	20,000 scfm
Chlorofluorocarbon vapors	36.0 lb/min; 842,400 lb/year
Fraction collected	0.85 = 30.6 lb/min
Chlorofluorocarbon recovery	95%; 680,238 lb/year

A. Value of recovered F-11 at 36¢/lb $244,886/year

B. Exhaust concentration

$$\frac{30.6\ \text{lb/min}}{137.4\ \text{lb/mol}} \times 359\ \text{ft}^3/\text{mol} \times \frac{559^\circ\text{R}}{492^\circ\text{R}} = 90.84\ \text{ft}^3\ \text{F-11 at }100^\circ\text{F}$$

$$\frac{90.84\ \text{ft}^3}{20{,}000\ \text{cfm}} = 4{,}542\ \text{ppm} \cong 0.067\ \text{psia}$$

Bed capacity at 100°F, 0.067 psia = 16.0% by wt. F-11

C. Plant investment required[a]

Complete carbon adsorption system with controls at $11.50/cfm including engineering design	$230,000
Pretreatment of vapors, add 10%	$23,000
Installation costs at 15%	$27,600
	$370,600
Carbon replacement after 8 years	($150,000)
Present value of deferred investment at 10%	$64,570
Total capital investment	$345,170

Table IV-15 (Concluded)

D. Annual operating costs[a]	
1 operator, 65 days	$6,000
Steam at 3.5 lb/lb F-11	$6,720
Cooling water and refrigeration	$3,200
Maintenance at 5%	$18,500
Insurance at 2%	$7,400
	$41,820/year
E. Equipment depreciation 15 years	
Discount rate 10%	
Capital recovery factor 0.13147 to recover investment and 10% interest over the 15-year life of equipment.	
F. Annual capital cost	$45,380
Annual operating costs	$41,820
	$87,200

$$\text{Savings/cost ratio} = \frac{\$244{,}886}{\$\ 87{,}200} = 2.80$$

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[a] Ventilation ducts and 30-hp fan not included, assuming an equivalent 20,000 scfm system already installed and in regular use.

Table IV-16. CALCULATED SAVINGS/COST RATIO FOR MOLDED FOAM PARTS

Basis: Postcure and flex section of model plant

Air flow rate	5,000 cfm
F-11 vapors	412 lb/day; 858 lb/min
Fraction collected	0.80; 0.686 lb/min
F-11 recovery	95%; 71,990 lb/year

A. Value of recovered F-11 at 36¢/lb	$25,917/year

B. Exhaust concentration

$$\frac{0.686}{137.4} \times 359 \times \frac{559°R}{492°R} = 2.04 \text{ cu ft F-11/min}$$

$$\frac{2.04}{5{,}000} = 407 \text{ ppm} \cong 0.006 \text{ psia}$$

Bed capacity of carbon at 100°F, 0.006 psia = 9.0% by wt.

C. Plant investment required

Use prepackaged sorption system for 5,000 cfm. Model 596 AD (Automatic Double Tank Package)	$46,500
Installation cost at 15%	$6,975
Replace carbon in 8th year	($32,500)
Present value of deferred expense	$13,120
Total capital investment	$66,595

D. Annual operating costs

No operator required; automatic cycling

Steam at 3.5 lb/lb F-11	$750
Cooling water and refrigeration	$1,150
Maintenance at 5%	$3,330
Insurance at 2%	$1,332
	$6,562

Table IV-16 (Concluded)

E.	Equipment depreciation	15 years
	Discount rate, 10%	
	Capital recovery factor 0.13147 to recover investment and 10% interest over the 15-year life.	
F.	Annual capital cost	$8,755
	Annual operating costs	$6,562
		$15,317

$$\text{Savings/cost ratio} = \frac{\$25{,}916}{\$15{,}317} = 1.69$$

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SECTION V

CLEANING AND DRYING SOLVENTS

This chapter discusses the sources of solvent emissions and possible methods for the control and/or recovery of emissions from the use of chlorofluorocarbons (primarily F-113) as cleaning and drying solvents.

Data in numerous reports and trade publications show clearly that the total consumption of chlorofluorocarbons as cleaning and drying solvents is relatively minor, both with respect to the overall consumption of these compounds and to the total quantity of solvents utilized for this application.1-3/ Solvent consumption accounts for approximately 5 to 9% of the total chlorofluorocarbon production according to different sources. The use of F-113 (and very small quantities of F-112) accounts for only about 5% of the total solvent consumption. The chlorinated hydrocarbons (e.g., trichloroethylene, methyl chloroform, etc.) are the dominant factors in this area.1/ F-113 and its azeotropes do not compete with the chlorinated hydrocarbons as general purpose solvents with industry-wide applications.1/ Because of its relatively high cost, F-113 is utilized primarily only in those applications where either a high level of cleaning quality is required or alternative solvents may pose a problem of compatibility with the materials of construction.

Chlorofluorocarbon solvents have basically five applications: (1) defluxing and electronics cleaning; (2) specialized degreasing; (3) displacement drying; (4) dry cleaning; and (5) miscellaneous specialty applications. Of these five areas, the first two represent, by far, the major sources of chlorofluorocarbon consumption in terms of total quantity. Specifically, the two major uses for F-113 based solvents are the defluxing of printed circuits and the general cleaning of components for the electronics industry. These solvents are well suited for this application because of their ability to remove the flux used in high-volume production of machine-soldered boards while, at the same time, displaying compatibility with the materials of construction. These solvents are also well suited for flux removal after hand-soldering operations associated with printed circuit rework and repair. Within the electronics industry and the military, large quantities of F-113 based solvents are used for the cleaning of printed circuits and electronic components intended for military use; as such, the solvent systems may have to conform to military specifications.

Dow Chemical Company recently made a study for EPA of the vapor-degreasing* area with respect to these same factors of emissions, their control, efficiency, and cost.4/ Their comprehensive report, however, was directed primarily at the chlorinated hydrocarbons. Through discussions with a major chlorofluorocarbon producer, manufacturers of vapor-degreasing equipment, and a manufacturer of vapor-recovery systems, it was determined that a considerable portion of the data developed for chlorinated hydrocarbons was equally applicable to F-113. Because of differences in the physical properties and the types of solvent systems (azeotropes), control of F-113 does require certain differences from that for chlorinated hydrocarbons. These differences are considered as part of the discussion of the appropriate recovery and/or reduction method. However, the discussions and data in the report by Dow Chemical Company have been incorporated, to a considerable extent, in the material presented in this section. A similar study has recently been completed by the Energy Systems Group of TRW, Inc., in which the sources of emission, solvent recovery and/or reduction methods, efficiency of methods, and cost parameters were evaluated for the dry cleaning industry.5/ In the TRW report, as in the Dow report, F-113 was not the primary solvent of interest because of the low volume consumed compared with the other solvents. However, the data and evaluations for F-113 were comprehensive and, thus, the discussion of the dry-cleaning industry, presented later in this section, incorporates a considerable portion of the evaluation presented in the report by TRW, Inc.

In the subsequent subsections of this section, each of the areas of room-temperature cleaning (commonly referred to as cold cleanings), vapor-degreasing, and dry cleaning will be discussed with respect to sources of solvent emissions, methods of emission reduction and/or recovery, efficiency of the methods, and cost factors related to the methods.

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* Hereafter in this section, the term vapor-degreasing will be used, but it is to be understood that this term includes both cleaning and degreasing operations.

COLD CLEANING

According to the Dow report, there are 1,026 plants in the United States that employ the use of F-113 or its azeotropes in cold-cleaning processes.[4] This figure represents about 7% of the estimated 14,955 plants that employ some type of cold-cleaning operation. The total quantity of F-113 consumed in the 1,026 plants was estimated at 19.5 x 10^6 lb or an average of about 19,000 lb/plant.[4] According to a major producer of chlorofluorocarbons, approximately 80% of the annual consumption of F-113 solvent in cold-cleaning equipment is for replacement of used solvent in existing equipment, and 20% is used to fill new equipment.[6]

Cold cleaning procedures represent the simplest mechanical operations of the three types of cleaning procedures to be discussed in this section. These operations generally include the processes of wiping, spraying (flushing), immersion (dipping), and solvent washers.[4,7] For F-113 systems, very little solvent is used for wiping parts, because the lower cost solvents are much more advantageous. The major F-113 producers have stated that approximately 90% of the F-113 consumed for cold cleaning purposes is pure (nonazeotrope) solvent, and the remaining 10% consists of azeotropic solvent systems.[6] This situation is essentially reversed for vapor-degreasing systems.

As discussed earlier in this section, the use areas for cold cleaning operations can be divided into military and nonmilitary oriented applications. In addition to its use with printed circuits, F-113 also finds usage in flushing operations on precision guidance equipment, such as gyroscopes, and in white-room cleaning associated with the aerospace program. Approximately 85 to 90% of all F-113 consumed in cold cleaning is estimated to be for military-oriented applications, and 10 to 15% for general benchtop cleaning purposes.[6] For military applications, particularly in the case of flushing operations on high-precision equipment, once the solvent has been used and becomes contaminated, it no longer meets the military specifications for that solvent and is downgraded. The downgraded solvent is then used either for other solvent applications which have less stringent military specifications or for nonmilitary applications. An estimated 75% of all F-113 consumed in military flushing and spraying applications is reused for other operations.[6]

Sources of Solvent Loss

The major sources of solvent loss from cold-cleaning operations are due to: (1) evaporation of the solvent; (2) solvent "dragout" losses on the cleaned parts; and (3) solvent disposal practices. Evaporation of solvent refers to volatilization from the liquid surface of the cleaning tank as opposed to the intentional discard of used, contaminated or excess solvent. Dragout losses refer to those emissions occurring as a result of solvent being retained in or on the part being cleaned. Parts withdrawn from cold cleaning systems often remain wet with solvent, or solvent is trapped in small holes or crevices in the part; this solvent ultimately evaporates uncontrolled into the atmosphere. The severity of dragout losses is very highly dependent upon the configuration of the article being cleaned. In the immersion cleaning of small parts, articles such as ball bearings would exhibit lower losses than an intricate part containing numerous small holes or crevices. For an average situation in which the part to be immersion-cleaned is neither overly simplified nor complex, the approximate percentage loss by each of the three major sources is: dragout, 50%; evaporation, 35%; and disposal, 15%.8/ For the cleaning of printed circuits, the dragout losses resulting from immersion cleaning are less severe than with other cleaning operations, and the percentage loss by each of the three sources has been estimated to be: evaporation, 40 to 45%; solvent disposal, 35 to 40%; and dragout, 20 to 25%.9/ The rationale for the high solvent disposal percentage from immersion cleaning of printed circuits and electronic components is that the manufacturers are producing high-quality low-reject-rate products, and that the consumption of cleaning solvent is secondary to this need.

A major electronics corporation has provided information on its F-113 cold-cleaning operations.10/ This cleaning process is used for metal components prior to their assembly in cathode ray tubes. These parts are generally comprised of cathode filaments, electrical contacts, support wires, grids, vanes for electrostatic guidance of the electron beam, etc. Since these parts are relatively simple pieces, being either flat or slightly bent, dragout losses are generally quite low unless the parts cluster together or the operator fails to allow sufficient drainage time. Approximately 70% of all of its cleaning operations utilize 5 to 10 gal. cold-cleaning tanks; the remainder is by vapor-degreasing. These cold-cleaning tanks are larger than the average type of F-113 cold-cleaning unit discussed below. For this cold-cleaning operation, solvent losses have been estimated as: evaporation, 80 to 85%; dragout, 10 to 15%; and solvent disposal, 5%. Solvent disposal is considerably lower than the figures stated above, because this company recycles the used solvent by in-house distillation.

For the cold cleaning of small parts, numerous small cleaning tanks are generally employed; the most common size of these tanks is 6 in. x 10 in. x 7 in. with a solvent capacity of approximately 1 quart.6/ These tanks are normally either placed on the workbench or in the immediate vicinity of the workers. Benchtop cleaning operations are basically uncontrolled, and eventually result in an almost 100% loss of solvent. Because of the number of these units and their very low volume of solvent per unit, very little of the used solvent is collected for distillation and reuse. Covers are supplied with virtually all cold cleaning units; however, it is not common practice for the covers to be utilized.[8] Cold-cleaning units also are typically filled reasonably close (to within 2 in.) to the top of the tank with solvent. This short distance from the solvent surface to the top of the tank (termed "freeboard" height) contributes significantly to the evaporation emissions of the solvent. The normal or "average" operation for small parts is to place the articles to be cleaned in a screen-wire basket, and to immerse the basket in the tank. Pumps are sometimes used to create turbulence in the solvent but more commonly, the baskets are manually raised and lowered to accelerate the cleaning action. Ultrasonic units are often used to assist in the cleaning action. The use of ultrasonics increases the evaporation rate of the cleaning solvent considerably. After a specified period of time, the baskets are removed, drained momentarily, and placed on the workbench.

For flushing operations, the situation is approximately the same as for immersion cleaning. If the article to be cleaned has numerous closely-spaced components, solvent will be trapped within these areas and eventually emitted into the atmosphere unless a proper drainage time is allowed. Very often, the drainage period is minimal, at best.

Conveyorized cold-cleaning equipment is used by high volume producers of machine soldered printed circuits and other electronic components, but the total number of such units is small. Excess flux and soil removal occurs when the articles are sprayed or brushed as they pass through the washer. The solvent drains to a holding tank and is recycled through the spray system. Solvent vapors are removed through the ventilation exhaust system.[4,11] Losses of solvent also occur by drag-out and by evaporation through the entrance and exit areas of the conveyor.[11]

Cleaning procedures which utilize F-113 in small volume aerosol or manual spray containers result in direct uncontrolled emissions into the atmosphere.

Although solvent losses do occur, solvent producers and equipment manufacturers generally say that users of F-113 solvent systems are more conservative in their operating practices than users of other solvents, primarily because of the nature of the business (precision electronic equipment, military applications, etc.) and the high cost of the F-113 solvent. This does not necessarily imply that good "housekeeping" practices are always employed by users of F-113 solvent systems.

Potential Emission Control Techniques

The potential emission control techniques discussed herein are basically those presented in the report by Dow Chemical Company but, in many cases, have been supplemented with data from additional sources. Careful attention to good "housekeeping" practices, while not a specific emission control, can certainly serve to reduce uncontrolled emissions and thereby assist the emission controls in reducing solvent loss.

Covers - Covers are supplied for essentially all cold-cleaning systems and should be employed to help reduce evaporative losses, particularly during nonshift periods, holidays, and weekends.[4] For any tank used in an irregular time sequence, covers should be employed if periods of nonuse exceed a half hour in length. Cold cleaning tanks are used for actual cleaning operations only about 25% of the work shift time.[4] It has been estimated that a well-fitted, gasketed cover could, conservatively, reduce evaporative emissions by about 60%.[8] Since covers are normally supplied with the unit, the only possible additional cost would be for a gasket seal inside the covers. However, the control of evaporative losses from cold-cleaning operations may not reduce the total emissions to the atmosphere significantly unless the control of waste solvent disposal is also controlled. Many of the current waste disposal methods for used solvent result in uncontrolled emissions to the atmosphere.

Drainage - Since solvent dragout losses represent the largest solvent loss mechanism, proper drainage is essential. For spraying operations, a coarse spray pattern should be employed and troughs provided to collect the overspray and drainage. A drainage area should be designated and utilized to provide an opportunity for the solvent to drain from the parts. Whenever possible, the parts should be rotated to assist in the drainage. These factors are equally applicable to flushing operations in which solvent entrapment can occur resulting in dragout losses.

For small parts cleaning involving the use of the small benchtop immersion tanks, rotation or shaking, if possible without incurring damage to the parts, should be employed to reduce solvent entrapment. Additional methods can be employed to help reduce dragout losses. The mesh of the wire screen of the basket could be changed, in some cases, and thus reduce the quantity of solvent being entrapped by the basket itself, although for very small parts, a fine wire screen is necessary. A simple addition to the current basket design could also be employed to help reduce dragout losses.[8] A hook device of some type could be attached to the basket to allow the basket to be hung on the end or side of the immersion tanks, and thus allow excess solvent to drain back into the tank. These devices are currently standard items on some types of units.[8] If such devices are not present, they could be added to existing units for a cost probably not exceeding $3 to $4.[8] Based on a current cost of about $50 to $75 for a 6 in. x 10 in. x 7 in. unit without ultrasonics and a cost of about $200 for a unit with ultrasonics, the added cost of $3 to $4 is quite nominal. If the basket was to remain in this position as each piece is removed, as needed, dragout losses could be substantially reduced. While exact figures for the reduction in dragout losses are not available and would be highly dependent upon the configuration of the part, a reduction of 50% or more may be possible in many uses.

Waste Solvent Recovery - Most cold cleaning operations seldom result in a contamination of the used solvent to a level greater than 10% by volume; this results in a used solvent which generally is 90% recoverable.[4] Simple distillation equipment can be used for F-113 solvents, because of its nonflammability. More expensive explosion-proof systems are available for flammable solvents. When the use of stills is considered for recovery of F-113, the type of soil (contaminant) and the initial or required purity or grade of the F-113 must also be considered. If the initial solvent was PCA (precision cleaning agent) grade F-113 and the soil was a very light weight oil, numerous (up to 30) distillations may be required to return the distillate to its original purity. On the other hand, if the original purity of the F-113 was not critical and the contaminates were heavy oils, a single distillation may provide an acceptable product.[12] Cold-cleaning operations are seldom equipped with distillation equipment except in the case of large conveyorized F-113 operations.

The economics of the in-house distillation of F-113 is based solely on the quantity of solvent which can be recovered for reuse. For these calculations, it is assumed that PCA grade F-113 is not required, and that a single distillation would provide a solvent of adequate purity. Adequate 60 gal/hr, water-cooled stills are available in the price range of approximately $3,000 to $4,000 or an average of about $3,500.[14] The same size still equipped with direct expansion refrigeration (5 h.p. air-cooled motor) would cost $6,700.[14] The following parameters have been used in this calculation:[4,14]

- An average still cost of $3,500
- Fifteen years still lifetime
- Fifteen percent of capital for installation cost
- Direct floor space of 3 ft x 4 ft

* Indirect floor space equal to 50% of direct (i.e., 6 ft^2)
* Building capital cost of \$25.9/ft^2
* Twenty-five years building life
* Insurance costs equal to 2% of equipment cost
* Maintenance costs equal to 4% of equipment cost
* Ten percent time value of money for annual costs

Using these parameters, the annual cost of a 60-gal/hr electrically heated, water-cooled still can be calculated as follows:[4/]

Capital equipment:	\$3,500	
Installation cost:	525	
	\$4,025	
Annual cost: \$4,025 x 0.13147*		\$529
Building capital: 18 ft^2 x \$25.9/ft^2 = \$466		
Annual building capital cost: \$466 x 0.11017**		51
Insurance (\$3,500 x 0.02)		70
Maintenance (\$3,500 x 0.04)		140
	Total annual cost	\$790

If an operating cost of \$0.20/gal is assumed, then, based on an F-113 value of \$6.60/gal,*** the value of the recovered solvent after operating costs is \$6.40/gal. Thus, the total annual cost of this type of installation could be recovered by the collection of 124 gal. of solvent. This quantity could be recovered in slightly more than 2 hr of continuous still operation.

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* The factor for returning principle plus 10% interest over a 15-year time period is 0.13147.

** The factor for returning principle plus 10% interest over a 25-year time period is 0.11017.

*** Price from Chemical Marketing Reporter (\$0.50/lb and 13.2 lb/gal), June 21, 1976.

Freeboard Height - Because of its potentially greater significance, a more detailed discussion of freeboard height and of its influence on evaporation rates is presented later in the subsection concerned with vapor degreasing. Most cold cleaning tanks have shallow freeboards, i.e., short distances from the solvent surface to the top of the tank. While this distance depends upon the size or volume displacement of the part to be cleaned, most users normally fill the tank to within about 2 in. of the top.[8] At this level, evaporative losses could be substantial, especially if air drafts are present. Data on solvent loss as a function of the freeboard height to tank width ratio is shown below in Figure V-1 for a F-113 system under static conditions at a room temperature of 72°F (22°C). These conditions represent typical solvent losses from a cold-cleaning unit while it is not in an operating cycle, i.e., no work is being cleaned. From the curve, it can be seen that as a freeboard height to width ratio of 1.0 is approached, the increments of solvent loss become smaller and that beyond a ratio of 1.0, very little decrease in solvent loss occurs.

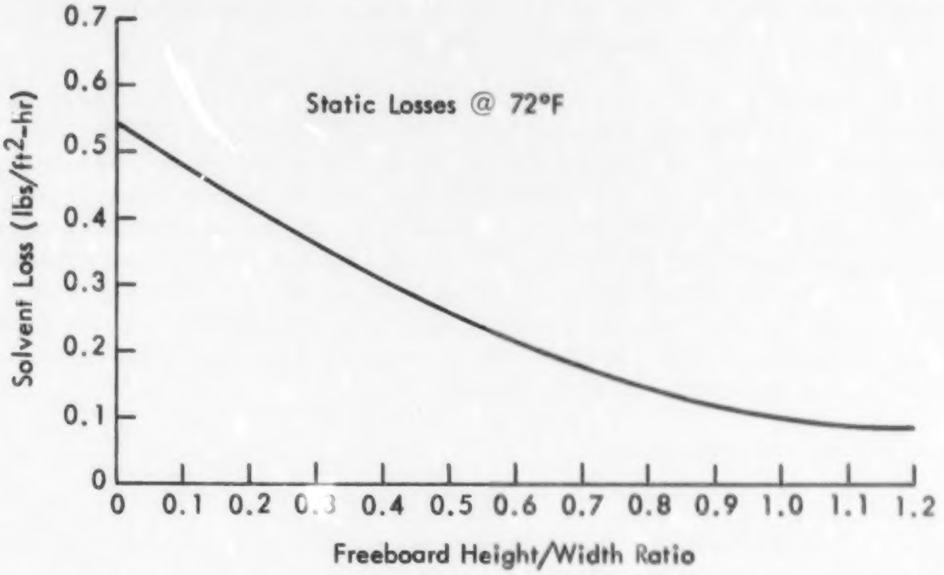

Figure V-1. Solvent loss as a function of freeboard height/tank width ratio

Using a 6-in. wide tank as a model and assuming that the solvent loss curve for static losses is valid for small width (6 in.) tanks, it can be calculated that increasing the freeboard height from 2 in. to

6 in. would result in a decrease in evaporative emissions of approximately 71%. To produce new tanks with a depth of 11 in. instead of 7 in. would result in an increased cost of the unit of about 20% or $10 to $15 for a current 6 in. x 10 in. x 7 in. cold cleaning unit costing $50 to $75.8/

Refrigerated Freeboard Coils - In the course of discussion of refrigerated freeboard chillers, Dow Chemical stated that the use of a refrigerated air blanket above a cold-cleaning tank would be expected to reduce the evaporative losses; but that, because of the intermittent use of most cold-cleaning operations, the use of a cover could be expected to provide a more efficient means of controlling the evaporative losses.4/ Since essentially all cold-cleaning units are equipped with covers, the addition of refrigerated freeboard chiller would appear to entail unnecessary expense and nonproductive use of energy and refrigerant.

Solvent Cooling - It is possible that the use of chilled water coils beneath the solvent surface could be used as a means to lower the temperature of the solvent, thereby decreasing its vapor pressure with a subsequent lowering of the evaporative emissions.

From a vapor pressure-versus-temperature curve, it can be estimated that decreasing the temperature of F-113 (Freon® TF) from 72°F (22°C) to 40°F (4°C) would result in a vapor pressure decrease of approximately 53% (6 psia to 2.8 psia).13/ As with refrigerated freeboard coils, the use of a cover would provide a more effective means for evaporative emission control without the added expense of solvent cooling coils. Additional factors would be the possible detrimental effects on the cleaning power of F-113 resulting from the decrease in solvent temperature, on the dragout losses, on the drying time for the cleaned parts, and on moisture condensation on the parts or the solvent.

VAPOR CLEANING AND DEGREASING

According to a published report on organic solvent metal cleaning operations, 1,014 plants in the United States employ the use of F-113, or its azeotropes, in vapor cleaning or degreasing operations.4/ This figure represents about 11% of the estimated 9,292 plants that employ one or more types of solvent for vapor cleaning and degreasing. The total quantity of F-113 based solvents consumed in the 1,014 plants was estimated at 36.6 x 10^6 lb, or an average of about 36,150 lb/plant.4/ According to a major manufacturer of chlorofluorocarbons and an equipment manufacturer, approximately 85 to 90% of the annual consumption of F-113 in vapor degreasing operations is for the replacement of used solvent in existing equipment, and the remaining 10 to 15% is used to fill new equipment.[6,14] With respect to the type of F-113 based solvents used in vapor degreasing operations, it has been estimated that approximately 90% of all F-113 defluxing in the electronics industry employed the use of azeotropes, and that for metal cleaning, a very large percentage of the F-113 used is in the form of the azeotropes.[14] Based on this information and comments from other users and equipment manufacturers, perhaps 85% or more of all F-113 used in vapor degreasing operations is in the form of an azeotrope. Pure F-113 is a very mild solvent so that its usage in this area is somewhat limited. A tabulation of F-113 azeotropes has been presented in an earlier report,[1] but perhaps three of the more common azeotropes are: 50% F-113 + 50% methylene chloride; 96% F-113 + 4% denatured ethyl alcohol; and 89% F-113 + 11% acetone.

In very simple terms, vapor degreasing is a largely physical method of removing soluble and insoluble soils from an essentially nonporous surface. The soiled article, at room temperature, is brought into contact with hot, nearly saturated, solvent vapor. The vapor condenses on the article's surface, and the liquid removes soil as it drains by gravity. Vapor degreasers are of two types: open-top machines and conveyorized units. There are many variations of each of these two types. For the use of F-113 solvents, approximately 95% of the vapor degreasers are open-top machines and 5% are conveyorized units.[14] The conveyorized units are used primarily by the large, high-volume electronic components manufacturers. Other users employ multiples of the smaller, open-top machines.

Of the open-top machines, the most prevalent units for this solvent are the medium sized, hand-operated immersion machines containing two sumps. In terms of actual dimensions, the most common F-113 units are either 14 in. x 20 in. x 12 in.[14] or 12 in. x 32 in. x 12 in.,[6] with 30 to 35 gal. solvent capacities. A typical two-sump F-113 vapor degreaser is shown below in Figure V-2.

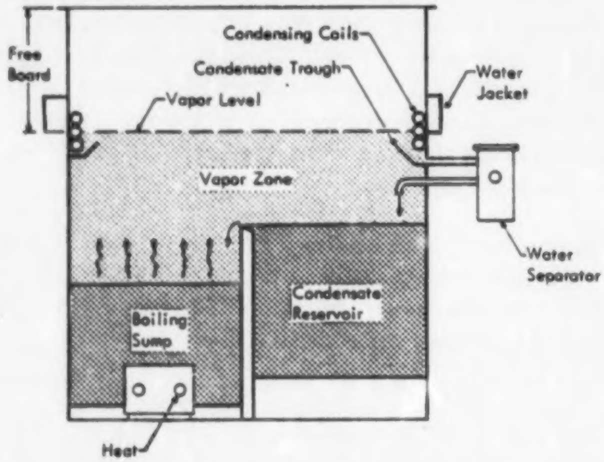

Figure V-2. Typical F-113 vapor degreaser

From the boiling chamber (sump), heavier-than-air solvent vapors rise to displace the air in the tank. The height, to which the upper level of the pure solvent vapors is allowed to rise, is controlled by the condenser coils located on the sidewalls of the degreaser tank. These condenser coils employ a heat-exchange fluid, normally water, and are designed so that they are theoretically capable of condensing all of the solvent vapor. Condenser coils vary in number and design depending upon the size of the equipment. A water jacket is also normally included to provide freeboard cooling and prevent heat convection up the tank walls. Beneath the condensing coils, a condensate trough collects liquified solvent vapor, along with some moisture from the air. This liquified solvent is passed through a water separator or desiccant dryer and returned to the immersion sump. For F-113 azeotropes containing ethanol, acetone, or other water soluble components, a silica gel or other desiccant dryer is necessary to prevent the removal of the water-soluble component with the aqueous phase.

The freeboard of a vapor degreaser is the distance between the top of the vapor zone and the lowest portion of the top of the degreasing tank. This distance is controlled by the placement of the condensing coils. For F-113 solvent systems, the minimum freeboard height should be 75% of the degreaser width, measured at the vapor-air interface. The freeboard height is very important in protecting the vapor zone from disturbance by air movement in the vicinity of the equipment. Disturbance of the vapor zone can lead to increased solvent vapor emissions into the atmosphere.

Conveyorized degreasers employ the same operational procedures as those for open-top degreasers, except that for conveyorized units, a large portion (sometimes all) of the manual handling of the parts has been eliminated. In the electronics industry, many of the F-113 users employ a special conveyor system designed for printed circuits, in which the boards are transported on a mesh belt through various combinations of immersion, spray, and vapor cleaning cycles. Other common units used with F-113 are the monorail conveyor and the crossrod conveyor systems.[4] Essentially all conveyorized degreasers are hooded or covered. This enclosure diminishes solvent losses from the system as a result of air drafts in the vicinity of the unit.

Design and operational guidelines for vapor degreasing machines have been detailed in the Dow report,[4] and a recent ASTM publication,[15] and have been summarized in brochures by an F-113 manufacturer.[16,17] These guidelines are briefly stated as follows:

1. Sump size: Surface area of immersion sump should be 50% greater than size of the workpiece. Sump depth should allow complete immersion of workpiece.

2. Solvent heating: Low-pressure steam is preferred. If electrical, heat flux should not exceed 25 to 30 w/in^2 of heater surface. Solvent boil-up rate (gallons/ hour) should equal volume of immersion sump.

3. Vapor zone: Vapor blanket should be sufficiently deep to cover workpiece completely during transfer between sumps.

4. Spray rinse: If used, all spraying should be completely within the vapor blanket.

5. Safety controls: Automatic heater cutoff switches should be installed both above the vapor zone to prevent vapor loss due to condenser failure and in the boil sump to prevent overheating from low solvent vent level or accumulation of soils.18/

6. Work load movement: Entry/exit speeds should not exceed 10 ft/min.

7. Machine installation: Machine should be placed in a draft-free, light traffic area with good ventilation.

For a more detailed discussion of these and other procedures, the recent ASTM publication is recommended.

Sources of Solvent Loss

The major sources of solvent loss from vapor degreasers are basically the same as those stated previously for cold-cleaning operations, namely: solvent evaporation; dragout; and solvent disposal practices. Leakages from sources such as pump packings, valves, gaskets, joints, sight glasses, etc., are normally very small, and are estimated to account for less than 1% of total solvent consumption.6/ Evaporation or diffusional losses result primarily from the mixing of solvent vapor with air or water vapor. Relative vapor density is an important factor in the consideration of losses due to diffusion. F-113 has a relative vapor density of 6.47 (air = 1), which is the highest of any common the common solvents used in vapor degreasing work.17/ This property makes it possible to maintain a stable, definite vapor line at the top of the vapor zone, which is less susceptible to disturbance from drafts and operational procedures.

Industry sources stated that a typical open-top vapor degreaser will show a solvent loss of about 0.2 $lb/ft^2/hr$ in idle condition, i.e., standing condition with no work being processed; under operating conditions, the solvent loss rises to 0.5 $lb/ft^2/hr$.[4,6] In terms of percentages, this means that of the total losses due to evaporation and dragout, approximately 60% of the loss is due to dragout. Under idle conditions, all losses are due to evaporative emissions. No consumption figures were stated for used solvent disposal. The figure of 0.5 $lb/ft^2/hr$ is a rather standard figure that has been used by industry. Not all vapor degreasers will experience the same loss rates owing to the differing operating conditions which would occur in actual industrial operations.[4]

Figure V-3 shows data for the quantity of F-113 solvent loss as a function of the condensing temperature at two different freeboard height/width ratios. These data are for a vapor degreaser under idle conditions and, as such, do not take into account losses that would occur during the work cleaning process, i.e., dragout, poor operating practices, etc.

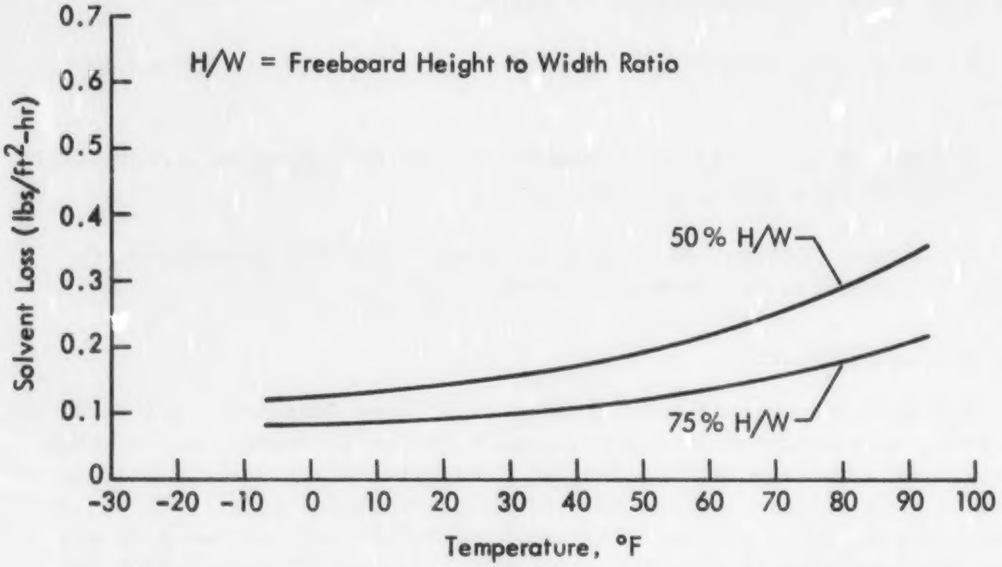

Figure V-3. Vapor degreaser solvent loss as a function of temperature

A representative of a major electronics and printed circuit manufacturer stated that losses from 100 and 150 gal. capacity, two-sump vapor degreasers, equipped with freeboard chillers, totaled approximately 3 to 4 gal/day.[19] This equipment does not employ lip ventilation, but each degreaser is hooded. Of these daily losses, the method of loss was estimated at 20 to 30% evaporation (diffusional losses), 60 to 70% dragout, and 5 to 10% solvent disposal. Dragout losses were principally due to solvent entrapment in cavities of the work being processed. For a continuous metal strip cleaner operating at a speed of 4 to 5 ft/min, the percentage of solvent loss was approximately 45 to 50% evaporative, 45 to 50% dragout, and 5 to 10% solvent disposal.[19]

According to the ASTM publication, the use of covered conveyorized vapor degreasers decreases solvent consumption by at least 20%/ton of parts cleaned.[15] This figure is not specific for F-113. A representative of a major electronics manufacturer states that, when using the 50% F-113 plus 50% methylene chloride azeotrope, the largest source of evaporative emissions is through the entrance and exit ports of the conveyor unit.[11]

Potential Emission Control Techniques

As in the section on cold-cleaning operations, the potential emission control techniques discussed herein are basically those presented in the report by Dow Chemical Company with supplemental data from industrial sources. The various systems and/or methods for the control of solvent losses from vapor degreasers that will be discussed are as follows:

- Operating practices
- Equipment
    - Carbon adsorption
    - Increased freeboard height
    - Refrigerated condensing coils
    - Refrigerated freeboard
    - Covers
    - Distillation
    - Offset sump systems

Operating Practices - Good operating practices as used here include methods of operating the equipment in a safe and economical fashion, while at the same time effecting emission control, but not including distinct recovery techniques. Good operating practices have been thoroughly discussed in other reports and publications[4,15-17] and a lengthy discussion here is unnecessary. However, a listing of these practices and very brief comments abstracted from the literature are given.

1. Draft: Draft is one of the most serious causes of excess loss; natural drafts should be held to a minimum; baffles may be constructed to divert air flow.

2. Dragout: Parts should be arranged to provide maximum drainage; work should remain in vapors until vapor temperature is attained; vertical hoists should not exceed a vertical speed of 10 ft/min.

3. Shock load: Size of work load should not exceed 50% of the tank area; if vapor zone drops more than 8 to 10 in., work load is excessive.

4. Load and basket design: Parts carrier should not create a "piston effect" on vapor zone during loading; carrier should be free drawing.

5. Spraying: Manual spraying must be done well into the vapor zone; fine, high pressure sprays should be definitely avoided.

6. Safety devices: A safety vapor thermostat should be used.

7. Leaks: Equipment should be inspected periodically for leaks at pump packings, valves, gaskets, sight glasses, and others; hot solvent evaporates rapidly so repairs should be immediate.

8. Maintenance: Equipment should be kept clean of accumulated oils, metal chips, etc.; heat exchangers should be descaled.

9. Covers: Topic will be discussed later.

10. Distillation: Topic will be discussed later.

An indication of the effect that good operating practices can have on solvent consumption is contained in a study conducted by one company that used 1,1,1-trichloroethane instead of trichloroethylene in a vapor degreaser.[20] In addition to some of the above guidelines, the degreaser was covered during low use and nonuse periods, the freeboard height was maintained at 50%, and only properly trained personnel were allowed to operate the degreaser. Over a 6-month operation test, solvent consumption decreased by 80%.

Carbon Adsorption - Carbon adsorption systems have been commercially available for about 17 years. Approximately 500 to 600 units are currently in use, but only about 15 to 20 are used in F-113 applications. Of the 15 to 20 units, only a few are being used for recovery from F-113 degreasing operations.[21] The principal reason is the cost of the unit.

The primary functions of a carbon adsorption system consist of two operations: adsorption and desorption.[4,22] Most of these systems consist of two tanks filled with activated carbon so that the adsorption and desorption processes can be run simultaneously to provide a continuous operation. Automatic valving is provided with the system, although manually operated systems are available. A diagram of a typical system is shown in Figure V-4. In the adsorption cycle, solvent-laden air enters the system, and passes over the activated carbon bed where the carbon collects the solvent; the cleaned air passes out the exhaust. A properly-sized carbon adsorption system will remove about 95% of the solvent present in the incoming air stream. The quantity of solvent present in the air stream is dependent upon many factors, including how closely the operators adhere to good operating practices as well as the efficiency of the ventilation system. One equipment manufacturer has given a rough estimate of 200 to 1,000 ppm for F-113 degreasers.[21] Once the carbon bed has adsorbed its working capacity of solvent (approximately 8% of the carbon bed weight for F-113), the air stream is switched to the second bed and the first bed is ready to be desorbed. The regeneration (desorption) cycle is performed by injecting low-pressure steam into the carbon bed to release the solvent from the bed. The resulting solvent-steam mixture passes into a condenser where liquefication occurs. A water separator collects the liquid and separates the two components by gravity.

In theory, the carbon adsorption system appears to be a rather simple procedure for F-113 systems; in practice, several other factors must be considered. Adsorption systems for F-113 are not the same as for chlorinated hydrocarbon solvents and are more expensive than the conventional units.[21] The carbon beds of the adsorption units tend to adsorb moisture, and during the desorption process considerable quantities of water can be adsorbed on the carbon bed. For the popular chlorinated hydrocarbon solvents, this does not present a serious problem because during the subsequent adsorption step, the chlorinated hydrocarbons will drive the water from the bed, and no decrease in adsorption capacity will be observed. When F-113 is used, water will effectively prevent its adsorption during the succeeding adsorption step unless the water is removed prior to the cycle. The moisture is effectively removed by treating the carbon bed with a stream of warm, dry air. Additional costs would be incurred for the extra blower, damper valves to allow the correct air flow, and a heat coil to provide the warm air. Since an additional step is

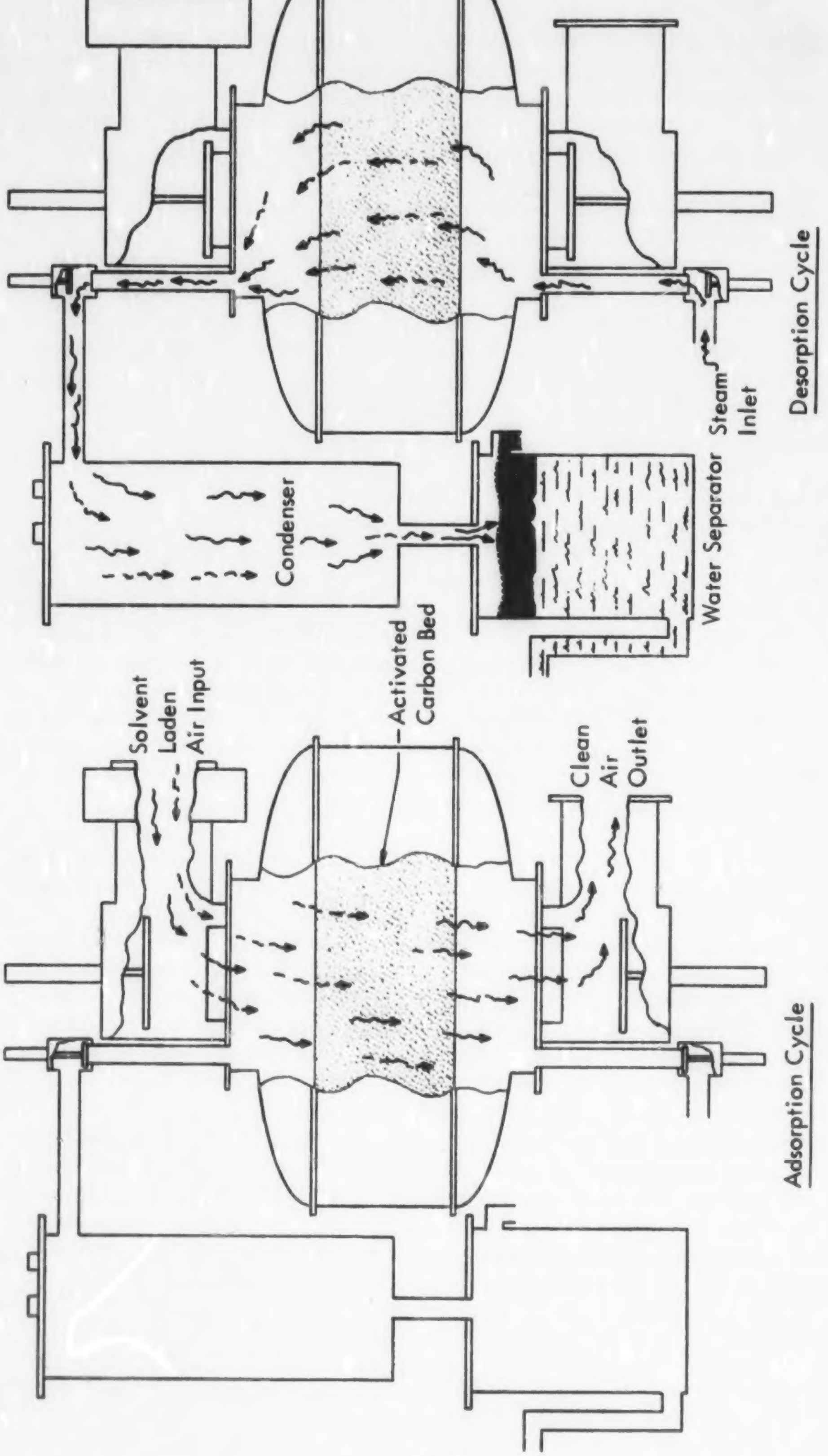
Solvent Laden Air Input
Activated Carbon Bed
Clean Air Outlet
Adsorption Cycle
Condenser
Water Separator
Steam Inlet
Desorption Cycle

Figure V-4. Typical carbon adsorber system

required in the process, the time period between adsorption steps is lengthened by approximately 15 min. If the bed dryer is employed prior to the adsorption step, it is estimated that a 95% capture efficiency can be expected for F-113.[21]

Most of the F-113 used in vapor-degreasing operations employs the use of F-113 azeotropes rather than the pure material. For certain azeotropes, carbon adsorption units can alter the composition of the azeotrope to a significant extent.[14,21] A water-soluble component of a azeotrope will be lost during the regeneration (desorption) and water separation process. For such materials, e.g., 96% F-113 plus 4% ethanol, 89% F-113 plus 11% acetone, etc., the azeotrope will be adsorbed on the carbon bed, but after desorption and water separation the resultant solvent will be pure F-113. The water-soluble component will be lost in the water phase. Thus, the carbon adsorption units are most feasible for pure F-113 and azeotropes containing nonwater-soluble components. For water soluble components, it would be necessary to reformulate the azeotrope after each adsorption/desorption process.

Carbon adsorption units are available in a number of sizes as shown in Table V-1. The correct size for an installation is dependent upon the volume of air flow required for ventilation, the quantity of solvent, and the type of solvent to be adsorbed.

A calculation of the theoretical cost and savings relationship for a carbon adsorption unit applied to an F-113 solvent system can be performed. The assumptions used to generate the calculated relationships are as follows:

1. Carbon adsorber pricing and operating data were obtained from the report by Dow Chemical Company and Vic Manufacturing Company.

2. Equipment calculated on a 15-year depreciation rate with 10% interest rate on the invested money.

3. Building space costs were not included since the adsorber unit does not require usable floor space. It can be installed on a loft, on the roof, or in other nonusable space.

4. Insurance was computed at 2%/year of the total equipment cost.

5. Maintenance was quoted by Vic Manufacturing Company at $100 to $150/year for the Model 536 AD.

6. F-113 pricing was obtained from the Chemical Marketing Reporter, June 21, 1976.

Table V-1. COMMERCIAL CARBON ADSORPTION UNITS[4,21]

			CFM			
Model	Lb of carbon per tank	Motor hp	Maximum - both tanks adsorbing	Minimum - one tank desorbing	Working bed capacity (F-113)	Price ($)[a]
534 AD	150	1.5	1,200	700	12	5,845
536 AD	350	3	1,300	800	28	9,320
554 AD	1,000	15	3,000	1,700	80	13,990
572 AD	1,500	20	5,500	3,000	120	22,085
584 AD	3,000	30	7,500	3,800	240	35,550
596 AD	4,500	50	10,000	5,000	360	46,445

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[a] Prices are FOB, Minneapolis, Minnesota, and do not include shipping and installation.

As stated previously, if a bed dryer is used prior to the adsorption process, a 95% capture efficiency is attained. However, a more important factor in emission control is the efficiency of the unit with respect to the overall solvent cleaning system. For F-113, the liquid dragout problems are not as severe as with the chlorinated hydrocarbon solvents because of the vapor pressure differential. Because of this differential and the overall smaller size of the degreaser with its better ventilation, an overall system efficiency of 60 to 75% is attained for F-113.[21] In these calculations the widely quoted figure for solvent emission of 0.5 $lb/ft^2/hr$ is assumed. A Model 536 AD carbon adsorption unit is chosen to be representative of the average size units that are employed with most F-113 systems but all of the various models can be employed with this solvent. Pure F-113 is chosen for the calculations rather than any of the azeotropic solvents since the required information is more readily available for this system than for the azeotropes. Except for price, it is doubtful that the parameters used in the calculations will vary to an appreciable extent for the nonwater soluble azeotropes. The calculated savings to cost ratio is shown in Table V-2. These calculations are an adaptation of those presented in the report by Dow Chemical Company.[4]

If the same calculation is performed on a basis of three shifts per day (6,000 hr/year), then the solvent savings per year are $3,510 and the total annual operating costs, based on 360 desorption cycles per year, are $2,407. This leads to a savings to cost ratio of 1.5.

A Model 536 AD, as used in Table V-2, requires a desorption cycle about once every 3 days. At this low desorption rate, it would be possible to use a smaller unit (534 AD) and desorb about everyday. While a daily desorption may pose some inconvenience, the operating costs would be significantly reduced. Assuming a Model 534 AD, 280 desorptions per year, and basically the same parameters as in Table V-2, a savings to cost ratio of 0.81 can be calculated. This compares with a ratio of 0.53 for the Model 536 AD used in Table V-2.

Increased Freeboard Height - Current OSHA regulations state that in any vapor degreasing tank the freeboard height shall be at least equal to one-half of the tank width at its narrowest point or at least 36 in. in height, whichever is shorter.[4] For F-113, industry recommendations have been that the freeboard height be at least 75% of the degreaser width. Several solvent producers, equipment manufacturers, and F-113 users implied that while a freeboard/width ratio of 0.75 is recommended, some of the F-113 vapor degreasers currently in operation do not meet this ratio. New equipment is generally manufactured to these standards, but older equipment still in use is likely to have a freeboard height/width ratio of approximately 0.5.

Table V-2. CALCULATED SAVINGS/COST RATIO FOR F-113 USING CARBON ADSORPTION

MODEL 536 AD

Assumptions

1. Degreaser loss rate is 0.5 $lb/ft^2/hr$
2. Overall recovery efficiency of 60%
3. Two-sump degreaser size of 14 in. x 20 in. (14 in/sump)
   (20 in. x 28 in.) = 1.67 ft x 2.33 ft = 3.9 ft^2
4. One shift per day (2,000 hr/year)

Solvent and cost savings

0.50 lb/ft^2-hr x 3.9 ft^2 x 2,000 hr/year x 0.60 = 2,340 lb/year

2,340 lb/year ÷ 13.2 lb/gal x $6.60/gal = $1,170/year savings

Annual costs

Capital

Basic Model 536 AD	$ 9,320		
Drying cycle (20%)	1,864		
	$11,184		
15% Installation	1,678		
Total	$12,862 x 0.13147[a]	=	$1,691
Equipment insurance (2%)	$12,862 x 0.02	=	257
Maintenance		=	150
Total capital cost per year			$2,098

Table V-2. (Concluded)

Operating (desorb 120 times per year)		
Steam - 90 lb/45 min desorption cycle 1,000 Btu/lb		
90 lb/cycle x 120 cycles per year x 1,000 Btu/lb x $\$2.3/10^6$ Btu	=	$ 25
Electric		
2 hp x 0.746 kwh/hp x 2,000 hr/year x $0.025/kwh	=	75
Water		
16 gpm x 60 min/hr x 90 hr/year x $\$0.04/10^3$ gal.	=	4
Total operating cost per year		$ 104
Total cost per year		$2,202

Savings/cost ratio

$$\frac{\$1,170}{\$2,202} = 0.53$$

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a/ 0.13147 is the factor for principal plus 10% interest over a 15-year period.

From data on solvent loss as a function of the condensing temperature for a vapor degreaser under idle conditions (see Figure V-3), an increase in the freeboard height/width ratio from 0.5 to 0.75 at a condensing temperature of 60°F (16°C) would result in a decrease in the evaporative solvent loss of approximately 36%. If it can be assumed that the shape of the curve for static losses would be the same at 60°F as that shown for 72°F (see Figure V-1), then an increase in the freeboard height/width ratio from 0.75 to 1.0 would show an emission control efficiency of about 35%. These figures are for static losses from a degreaser under idling conditions, and do not include losses attributable to dragout, etc.

For large vapor degreasers, increases in freeboard height may require additional installation costs because of increased ceiling height, increased pit depth, or increased platform height. It has been recommended that the elevation of the top of an open-top degreaser be 42 in. above either the floor level or operating level.[15] Generalized cost estimates for this type of construction cannot be made since these costs would be specific to a given facility. For the calculated savings/ cost ratio developed in Table V-3 for F-113, only the cost of the additional stainless steel plus welding at the time of manufacture is considered. A cost of $10/ft^2 of 12 gauge stainless steel has been used.[4]

In addition to the calculated saving-to-cost ratio shown in Table V-3, a similar calculation for an increase in the freeboard height/width ratio from 50 to 100% (60% emission control) would show an annual solvent savings of $468 with an annual cost of $10 for a savings-to-cost ratio of 46.8. As shown in Figure V-1, there appears to be little to be gained in terms of solvent conservation by increasing the freeboard height to width ratios appreciably above 1.0. While these data are for cold-cleaning systems, the conclusion is equally valid for vapor degreasers. Degreaser manufacturers believe that there is little to be gained by increasing the freeboard height above a maximum of 4 ft, regardless of the size of the vapor degreaser.[14] A solvent producer quotes a maximum height of 3 ft, regardless of size.[6]

Refrigerated Condensing Coils - In this subsection the discussion will center on the use of cooling devices to decrease the temperature of the vapor condensing coils to slightly above 32°F (0°C). One of the methods for this decrease in temperature is by direct expansion refrigeration but only to temperatures of approximately 35°F (2°C). (In this context, the refrigeration discussed here should not be confused with a refrigerated freeboard chiller or "Cold Trap," which employs a completely separate and different set of cooling coils placed near the top of the degreaser and operates under a different principle at temperatures of -20°F (-29°C). The refrigerated freeboard concept will be discussed in the next subsection.)

Table V-3. CALCULATED SAVINGS/COST RATIO FROM INCREASED FREEBOARD HEIGHT

Assumptions

1. F-113 vapor degreaser size is 20 in. x 28 in. (3.9 ft^2)
2. Increase freeboard ratio from 75 to 100% (35% emission control)
3. Evaporative solvent loss is 0.2 lb/ft^2-hr (see page V-23)

Estimated annual solvent loss (40 hr/wk)

0.2 lb/ft^2-hr x 3.9 ft^2 x 2,000 hr/year = 1,560 lb/year consumed

1,560 lb/year x 0.35 = 546 lb/year saved

546 lb ÷ 13.2 lb/gal x \$6.60/gal = \$273/year saved

Capital cost

Freeboard increased from 15 to 20 in. (0.42 ft)

0.42 ft x 8 peripheral feet x \$10/ft^2 = \$34

Annual cost

Capital: \$34 x 0.13147[a] =	\$4
Insurance (2% of capital) =	1
Total cost	\$5

Savings/cost ratio

$$\frac{\$273}{\$5} = 54.6$$

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[a] 0.13147 is the factor for principal plus 10% interest over a 15-year period.

As discussed previously in the general description of vapor degreasers, the primary cooling coils are utilized to control the top of the vapor zone and to reduce evaporative emissions from this zone. Both the condensing temperature and the freeboard height have a significant effect on the quantity of evaporative emissions. The approximate quantity of solvent loss as a function of condensing temperature for two different freeboard height/width ratios was shown in Figure V-3. For the higher boiling chlorinated hydrocarbon solvents, ordinary tap water in the primary condensing coils normally provides sufficient cooling. In many instances tap water is also used for F-113 systems. However, at least one equipment manufacturer recommends 60°F (16°C) or lower cooling water for pure F-113 and the ethanol or acetone azeotrope.[14] For the F-113 + methylene chloride azeotrope, a cooling water temperature of 50°F (10°C) is recommended. To achieve these recommended temperatures, it may be necessary to replace the use of tap water in the primary condensing coils with either chilled water or direct expansion refrigeration to condense the solvent vapors. As shown in Figure V-3, a decrease in the temperature in these coils can have a marked effect on the rate of evaporative emissions.

Direct-expansion refrigeration operates on the same principle as all other types of refrigeration. Instead of water in the primary condensing coils, a refrigerant fluid is used, and a small compressor unit is attached directly to the vapor degreaser. Temperatures are thermostatically controlled to preset values. It is not recommended that a water-cooled system in operation be modified and retrofitted with direct-expansion refrigeration.[14] For those units in operation, it is advisable to add a water chiller unit instead of the refrigeration unit because of moisture in the system and corrosion and scaling from the prior use of water. Water-chiller units operate on the same principle as the water chillers described earlier in this report in the chapter on refrigeration. Basically, a small refrigeration unit is used to chill the water, which is then circulated through the condensing coils.

The addition of a direct expansion refrigeration system would increase the cost of a basic vapor degreaser by approximately $1,700.[14] Water chiller units would cost about $1,850 to $1,900, exclusive of customer labor for installation. Calculated savings-to-cost ratios for each of these units are shown in Table V-4.

In these calculations an initial cooling water temperature of 60°F (16°C) has been assumed in accordance with the recommendations of an equipment manufacturer. The percent emission control factors are based on this temperature. However, if ambient tap water at 72°F (22°C) is used for cooling the primary condensing coils, then the percent emission

Table V-4. CALCULATED SAVINGS/COST RATIO FROM REFRIGERATED CONDENSING COILS

Assumptions

1. Degreaser size of 20 in. x 28 in. (1.67 ft x 2.33 ft = 3.9 ft^2)
2. 75% Freeboard height/width ratio
3. One working shift per day (2,000 hr/year)
4. Solvent loss is 0.5 lb/ft^2-hr
5. Initial cooling water temperature of 60°F (16°C)

Estimated annual solvent loss

0.5 lb/ft^2-hr x 3.9 ft^2 x 2,000 hr/year = 3,900 lb/year

Estimated annual cost conserved

1. Direct expansion refrigeration operated at 35°F (1°C) - 29% emission control (Figure V-3)

   3,900 lb/year x 0.29 ÷ 13.2 lb/gal x $6.60/gal = $565/year

2. Water chiller operated at 40°F (4°C) - 21% emission control (Figure V-3)

   3,900 lb/year x 0.21 ÷ 13.2 lb/gal x $6.60/gal = $409/year

Annual costs

Direct expansion refrigeration

Capital costs

Equipment: $1,700 x 0.13147[a/]	=	$223
Insurance (2%)	=	34
Inspection and maintenance[b/]	=	50
Total capital costs		$307

Table V-4. (Concluded)

Operating costs		
Electricity: 0.248 kwh[c/] x 2,000 hr/year x $0.025/kwh	=	$ 12
Total annual costs		$319
Water chiller		
Capital costs		
Equipment: $1,875 x 0.13147	=	$246
Insurance (2%)	=	38
Inspection and maintenance[b/]	=	50
Total capital costs		$334
Operating costs		
Electricity: 0.249 kwh x 2,000 hr/year x $0.025/kwh	=	$ 12
Total annual costs		$346
Savings/cost ratio		
Direct expansion refrigeration		
$\frac{\$565}{\$319} = 1.8$		
Water chiller		
$\frac{\$409}{\$346} = 1.2$		

[a/] 0.13147 is the factor for principal plus 10% interest over a 15-year equipment lifetime.

[b/] Mr. Richard Clement, Detrex Chemical Industries, Inc., Detroit, Michigan.

[c/] Basic data supplied by Reference (b).

control factors would be 31% for the water chiller at 40°F (4°C), and 38% for direct expansion refrigeration at 35°F (1°C). Using the two emission control factors for 72°F and performing the same calculation as in Table V-4, the direct expansion refrigeration would show a savings-to-cost ratio of 2.3, and the water chiller a ratio of 1.7.

With most vapor degreasers, the top of the vapor zone is approximately in the middle of the primary condensing coils, which means that about 50% of the coils are above the top of the zone. Employing cooling temperatures slightly above 32°F (0°C) has the added advantage of providing a small zone of cool air above the vapor zone. This cool air assists in the prevention of vapor loss during the entrance and exit of the parts to be cleaned. A concise evaluation of the control efficiency of this type of cool air blanket is difficult to assess since it relies very heavily on operating procedures and the size of the parts. One example of a combination of factors is a midwestern company that cleans printed circuits with the F-113 plus ethanol azeotrope. The company installed a new vapor degreaser equipped with direct expansion refrigeration in the primary condensing coils. With the new machine, operating practices also improved over those used with the old machine. Solvent consumption decreased from approximately 1,375 gal/year to about 550 gal/year or about 60%.[23/] While these decreases cannot be directly attributed to one specific control measure, they do provide an indication of the solvent savings that can occur.

Refrigerated Freeboard Chillers - In the context of this section, this terminology is meant to apply to those devices operating at temperatures of 32°F (0°C) or colder. The device, termed "Cold Trap," was introduced over 10 years ago but has encountered some sales resistance in the intervening years.

While this emission control device operates in conjunction with the normal primary condensing coils, it is based on a completely different principle.[14,24/] It consists of a set of coils in a compact shield placed on the degreaser freeboard several inches above the primary condensing coils. A small refrigeration unit is located near the degreaser to circulate the refrigerant through the coils. Whereas the primary condensing coils control the upper limit of the vapor zone by condensing the solvent vapors, the refrigerated freeboard chiller coils, operating at -20°F (-29°C), form an inversion layer of cold air above the solvent vapor line to inhibit solvent vapor diffusion from the degreaser. Any moisture in the air and solvent vapor present above the vapor line freezes on the refrigerated coils. These systems are designed with an automatic defrost cycle to periodically melt the frozen accumulation. The liquid returns to the degreaser condensate trough and restores the efficiency of the heat exchange surface. During this defrost cycle, the unit is out of service and the heat generated by defrosting may add slightly to the emission level. The liquid water and solvent produced by the defrost cycle is directed from the condenser collection trough, through the water separator, and into the rinse sump. If the water separator is not sufficiently large, water contamination of the sump liquid will result. A secondary water separator may be necessary on some equipment to insure complete separation. This is especially critical for F-113 azeotropes containing water-soluble components. Desiccant dryers must be used to avoid destroying the azeotrope. In addition, water contamination of F-113 vapor degreasing solvents can also lead to equipment corrosion and increased solvent evaporation.

The "Cold Trap" system has been accepted by the New York Department of Labor in lieu of an exhaust system for controlling solvent emissions generated in open-top vapor degreasing units. The only stipulations to this acceptance are that the temperature of the cold air blanket must be at least 70% lower than the boiling point of the solvent, and that the circulating refrigerant must be 0°F (-17.8°C) or colder. The "Cold Trap" system has been the center of considerable controversy during its existance.24/

A calculated savings-to-cost ratio for the "Cold Trap" is presented in Table V-5. Data on the pricing of refrigerated freeboard chillers, design parameters, refrigeration coil pricing, and an overall system efficiency of 35% were obtained from the report by Dow Chemical Company.4/ A 15-year equipment life, 6% of capital cost for insurance and maintenance, and a 10% interest rate on capital costs were assumed.4/ Since most "Cold Traps" have been retrofitted to existing systems, the pricing used in this calculation has been based on this mode of installation. If this equipment were to be installed on a new vapor degreaser during its construction, the incurred cost would be approximately 67% of the price shown in Table V-5.4/ The savings-to-cost calculation is made for the most common size F-113 vapor degreaser. Data for larger size units can be compiled from the previously-referenced report on chlorinated hydrocarbon solvents.4/

Covers - F-113 vapor degreasers normally are equipped with manually operated covers. An F-113 solvent producer stated that covers were normally available as an additional option.6/ However, a major vapor degreaser manufacturer said that all of the F-113 degreasers built by that company are equipped with a roll cover and that metal covers are available as an added option.14/ The roll covers operate on a principle very similar to that of a windowshade. For covers greater than 4 ft^2 in area, an automated power-driven assembly would be recommended.6/

Table V-5. CALCULATED SAVINGS/COST RATIO FOR REFRIGERATED FREEBOARD CHILLERS

Assumptions

1. Degreaser size of 20 in. x 28 in. (3.9 ft^2)
2. One working shift per day (2,000 hr/year)
3. Solvent loss is 0.5 lb/ft^2-hr
4. 35% System control efficiency

Estimated annual solvent savings

0.5 lb/ft^2-hr x 3.9 ft^2 x 2,000 hr/year = 3,900 lb/year

3,900 lb/year x 0.35 ÷ 13.2 lb/gal x $6.60/gal = $682/year

Total capital cost

Compressor (includes installation) = $2,635

Coils (8 ft x $32/ft) = 256

Total cost $2,891

Annual cost

Capital cost: $2,891 x 0.13147[a] = $380

Operating: 0.5 hp x 0.746 kwh/hp x 8,760 hr[b] x 0.025/kwh = 87

Insurance and maintenance (6% of capital): 0.06 x $2,891 = 173

Total annual costs $640

Savings/cost ratio

$$\frac{\$682}{\$640} = 1.1$$

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[a] 0.13147 is the factor for principal plus 10% interest over a 15-year equipment lifetime.

[b] 24 hr/day; 365 days/year.

Because of the generally smaller size of F-113 degreasers as compared to those using chlorinated hydrocarbon solvents, covers are much more convenient to operate than for the larger degreasers. Because of this convenience, the actual usage of covers is much more prevalent with F-113 systems than with the chlorinated hydrocarbons; it has been estimated that approximately 50% of the current users cover their systems during periods of nonuse.[14,21]

For a 24 in. x 32 in. F-113 vapor degreaser, a cover could be added at a cost of approximately $150 to $200.[14] As the size of the open top degreaser increases, the cost of a cover can become appreciable. It has been reported that a cover for a 2.5 ft x 6 ft open top degreaser may cost $1,500; a 4 ft x 12 ft unit costs $2,250; and a 5 ft by 40 ft would cost $5,000.[4] These costs are variable, depending upon whether they are retrofitted to existing systems and upon the material of construction. The larger covers are, of course, all power-driven, automated mechanisms which would contribute to their increased cost.

While it has been stated that the use of covers is a very favorable emission control device,[14] no information regarding any extensive studies was available with respect to precisely how effective this emission control technique would be for F-113 systems. An effectiveness of 35% has been stated for the chlorinated hydrocarbons.[4] This efficiency may be somewhat low for the smaller F-113 systems.

The specific type of cover and method by which it is used play an important role in the emission control efficiency. Elastomer-gasketed metal covers would provide a good seal against vapor leakage during nonuse periods. However, if these covers are simply lifted from the top, the rush of incoming air created by the lifting process will disturb the vapor-air interface and create a "piston effect", with a resultant large increase in solvent-vapor concentration in the air space above the degreaser. Lifting the cover in a slow and gentle manner would eliminate or significantly reduce this "piston effect"; however, following this procedure would be entirely dependent on the machine operator. The roll-top cover reduces the effect of the incoming air, and hence the disturbance of the vapor-air interface, since the top of the degreaser is not opened all at once to the atmosphere. If the roll-top cover is not sealed by an elastomer gasket, leakages can occur when the top is closed. A roll-top cover with an elastomer gasket is used by some manufacturers of F-113 vapor degreasers. A laboratory scale study of the effectiveness of covers has been conducted that indicates an emission control effectiveness of 50% may be somewhat conservative, but would represent a generally acceptable value.[25]

The calculations shown in Table V-6 are for a typical 20 in. x 28 in. (3.9 ft^2) F-113 vapor degreaser in use for 8 hr/day. The solvent loss is 0.2 lb/ft^2-hr, which is the quoted figure for a degreaser under idle conditions.

Distillation of Used Solvents - Soils removed during the cleaning operation will accumulate in the boil sump of a two-sump vapor degreaser. A typical F-113 vapor degreaser was depicted earlier in Figure V-2. Ultimately, the dirty solvent must be either discarded or reclaimed. As the control of solvent emissions directly into the atmosphere increases, the quantity of used, or dirty, solvent will inherently increase. Thus, the prevention of environmental emissions from discarded solvent becomes increasingly important.

For general cleaning operations, the oil contamination of the F-113 in the boiling sump is generally limited to a maximum value of 25 to 30%; however, this value may be substantially lower for critical cleaning operations.[17/] When this maximum value has been attained, the boiling sump must be cleaned to dispose of the accumulated soils. Because F-113 is relatively low boiling, stable, and nonflammable, reclamation can be simple if proper distillation equipment and operating procedures are used. A number of options are available for the partial or complete recovery of F-113 from a dirty solvent system.

One method employs the use of the two-sump vapor degreaser itself for the partial recovery of the F-113 solvent.[26/] The two-sump vapor degreaser is analogous to a simple one-plate still; and, using the high temperature safety controls in the boiling sump, partial recovery of the solvent can be achieved. While the recovered solvent may not meet new product specifications in some instances, the recovery solvent is normally satisfactory for most uses. This recovery method must be conducted while the equipment is not in use, since cleaning procedures cannot be conducted while the reclamation is in progress. Very simply, the procedure consists of removing the clean solvent from the condensate chamber and the rinse sump. The safety control in the boiling sump is then increased in temperature increments up to a maximum temperature of 140°F (60°C). At this temperature, the composition of the liquid in the boiling sump is approximately 50% F-113 and 50% soil. The distilled F-113 collects in the condensate chamber and the rinse sump. At this point, the liquid is drained from the boil sump and collected for further treatment or disposal. Fresh solvent is added to the distilled solvent until the normal liquid level is reached and the safety control is reset to its original temperature.

Table V-6. SAVINGS TO COST RATIO FOR THE USE OF COVERS

Assumptions

1. 50% Emission control effectiveness
2. 0.2 lb/ft^2-hr solvent loss
3. One shift per day (2,000 hr/year)

Estimated annual solvent use

0.2 lb/ft^2-hr x 3.9 ft^2 x 2,000 hr/year = 1,560 lb/year

Estimated annual cost saved

1,560 lb/year x 0.5 ÷ 13.2 lb/gal x \$6.60/gal = \$390/year

Annual costs

Capital costs: \$175 x 0.13147 = \$23

Insurance (2%): \$175 x 0.02 = 4

Maintenance (4%): \$175 x 0.04 = 7

Total annual cost \$34

Savings/cost ratio

$$\frac{\$390}{\$34} = 11.5$$

In-house distillation can be conducted with an external still, using either the original dirty solvent or the liquid remaining from distillation in the degreaser. In either case, the solvent is collected in drums or pumped directly from the degreaser to the still system. Distillation stills are normally incorporated directly into F-113 conveyorized vapor degreasers and into open-top units with a solvent capacity greater than 60 gal.[6] For the smaller units, however, a centralized still would be used. The economics of the use of a still were previously discussed in the section concerning cold-cleaning applications. With a normal stainless steel F-113 still, approximately 75% of the solvent can be reclaimed by means of low-pressure steam heating. To attain maximum recovery of solvent, live-steam injection into the bottom of the still should begin when the still temperature reaches 170 to 180°F (77 to 82°C). Approximately 90% solvent recovery can be attained at a still temperature of 120°C.[17]

A contract distillation service can be used to reclaim used solvent. A number of solvent reclaimers are available, e.g., Chem-Trol Pollution Services, Inc., Custom Organics, and Solvent Recovery of New Jersey. The cost of the reclaimed solvent is somewhat dependent upon the type of soils present in the solvent and the desired purity of the final product. However, in almost all cases, the price of the reclaimed solvent is less than that of new solvent.

According to a manufacturer of vapor degreasing equipment and a solvent producer, very little of the dirty F-113 solvent from the small systems (capacity < 60 gal.) is distilled or reclaimed.[6,14] For conveyorized systems and open-top degreasers of greater than 60-gal. capacity, stills are normally incorporated into the system, and distillation of used solvent occurs more frequently.

Offset Sump Systems - In certain instances, it may be possible to use a vapor degreaser with an offset vapor generating sump (boiling sump). A simplified diagram of this system is shown below in Figure V-5.

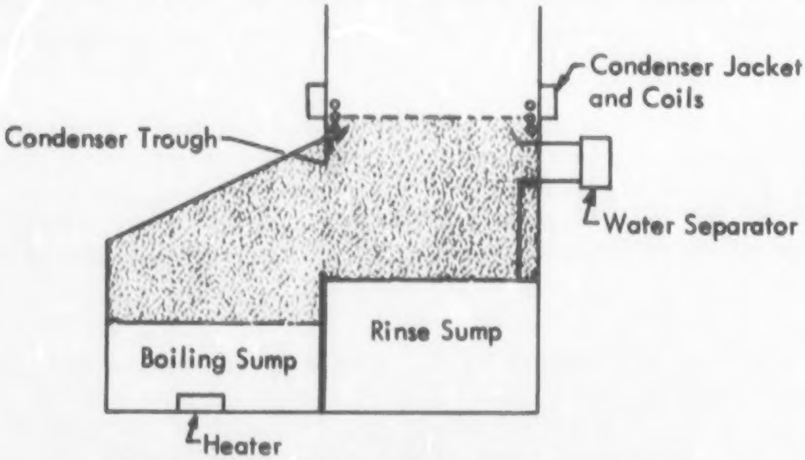

Figure V-5. Offset sump vapor degreaser

The difference between this unit and the normal open-top vapor degreaser lies in the fact that, in this case, the boil sump is essentially covered and the only area with a vapor-air interface is above the rinse sump. This reduced vapor-air interfacial area results in a decrease in solvent loss by evaporative emission. Single sump units, with solvent spray capabilities, have also employed this type of design. Where it can be employed, this type of system could reduce vapor-air diffusional emissions by approximately 50% as compared to those of a conventional fully open-top machine.[17]

The use of this type of system is not extensive at the present time. Those systems in service are larger machines with a 2 ft x 3 ft or larger opening and a solvent capacity of 250 gal. or more. Compared to a conventional fully open-top machine of the same solvent capacity, the offset sump design generally costs approximately 10% more than the conventional machine.[25]

DRY CLEANING INDUSTRY

A thorough study of the various solvents, including F-113, used in the dry cleaning industry was performed by the Environmental Engineering Division of TRW, Inc.[5] Their study was aimed at the support of new source performance standards for the dry cleaning industry. Within the scope of the study the following areas were evaluated: dry cleaning processes and emissions, emission control technology, plant modifications, environmental impacts, and economic impacts. To avoid a duplication of effort, the information to be presented herein on the use of F-113 in the dry cleaning industry was extracted to a large extent from the TRW study.

F-113 is the only chlorofluorocarbon used in the United States for dry cleaning purposes. It is sold as a charged (about 0.1% cationic detergent added) dry cleaning agent under the tradename of "Valclene®."* The dry cleaning industry consumes very small quantities of F-113 as compared to the consumption of Stoddard solvent and perchloroethylene.[1,2] For 1974, the consumption of F-113 in this industry was approximately 2 to 4 million pounds.[1]

The dry cleaning industry has three types of operations: coin-operated, commercial plants, and industrial operations. At the present time, F-113 is used only in the coin-operated and commercial operations. According to 1972 government statistics, the total number of coin-operated establishments was 17,550 and the total number of commercial plants was 28,422.[5] For coin-operated installations, in which the general public operates the equipment, less than 10% of these employ the use of F-113; for commercial plants, operated by trained employees, approximately 45 to 50% are F-113 type machines.[21] In several commercial installations, machines of the size used for coin-operated establishments are employed but are operated only by trained personnel.

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* "Valclene®" is a trademark of E. I. du Pont de Nemours and Company.

Dry cleaning machines are basically of two types: transfer machines and dry-to-dry machines. Because of the high cost of F-113 cleaning solvent, compared to perchloroethylene or Stoddard solvent, excellent solvent recovery must be attained to allow these machines to be competitive. Because of this, all F-113 machines are of the dry-to-dry type, in which the washing and drying operations are performed in a single unit. Thus, all F-113 machines have a built-in solvent recovery device. During the drying cycle of these machines, the air flows from an air heater through the cleaning drum (containing the cleaned material), a dry valve, and a blower to the solvent recovery device. After the solvent has been removed from the air stream, the air flows back to the heater and the cycle is repeated. The average temperature of the heated air at the heater discharge is 120°F (49°C); in the cleaning drum, the air temperature is about 100°F (38°C). In the early models of the F-113 machines, carbon adsorption units were used for solvent-vapor recovery from the air stream; however, newer models employ the use of refrigerated coils in the closed loop system. These units also include a filtration unit and a solvent distillation system. The current models are completely closed to the atmosphere during operation. F-113 machines also are sold only as complete packages.

For F-113 machines, the drying time and total cycle time for a load of clothes are considerably shorter than for the same size load when perchloroethylene is used. This is due to the higher evaporation rate of F-113. As a consequence, the capacity can be smaller than for perchloroethylene units since more loads can be run with F-113 within the same time period. For F-113, the most common size units are those with 12- and 25-lb capacities.

Solvent Consumption and Possible Emission Sources

As stated earlier, all F-113 units are dry-to-dry machines with built-in solvent recovery methods, either dual tank carbon adsorption or refrigeration condensation. The conversion from carbon adsorption methods to refrigeration condensation occurred because (1) the carbon adsorber was overly complex for coin-operated installation; (2) if F-113 and perchloroethylene were used in the same plant, solvent contamination could occur; and (3) the adsorber units required too much floor space, as well as high steam consumption. However, with either type of recovery unit, F-113 machines show very low solvent consumption rates compared to machines using the other two solvents.[5]

Because dry cleaning operation with F-113 is relatively new compared to operation with the other two solvents, little information concerning typical solvent consumption rates is available. Many dry cleaning plant operators discuss solvent consumption in terms of "mileage", but this practice is being discouraged.[27] "Mileage" is the number of pounds of fabric cleaned per 52 gal. drum of solvent consumed. Mileage is proportional to the reciprocal of the solvent consumption rate (in pounds of solvent per 2,000 lb of fabric cleaned). Some of the solvent consumption rates that have been quoted are shown below in Table V-7. For perchloroethylene, a typical solvent consumption rate for a unit without a carbon adsorber is 203, and with an adsorber, the value is 168.[5] To put the F-113 values in a different perspective, if one assumes an average solvent consumption rate of 71, this corresponds to the total loss of approximately 0.04 lb of solvent per pound of clothes cleaned. In terms of volume, this 0.04 lb total loss is equivalent to about 0.3 ounces (~ 9 cc) per pound of clothes cleaned.

Table V-7. F-113 SOLVENT CONSUMPTION RATES[5]

Tester	Solvent consumption[a]	Comments
IFI Research Center	35	Laboratory tests by highly trained personnel
Du Pont	60	Certification standard for new machines
Vic Manufacturing	37	Laboratory tests by highly qualified personnel
Du Pont and EPA	88-12 lb capacity 71-25 lb capacity	Units tested in a plant operation by Du Pont and EPA personnel; these figures probably representative of field performance

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[a] Pounds of F-113 per 2,000 lb of cloth cleaned.

Possible solvent emission sources from F-113 dry cleaning machines are stated to be:[5,21]

- Solvent retention in the cleaned fabric.
- Vapor emission losses from the cleaning drum caused by door-opening between loads.
- Solvent retention in the filter cartridges.
- Solvent retention in sludge from the distillation system.
- Mechanical leakages, including seals and gaskets due to faulty construction or improper fit.

According to the TRW study, solvent loss due to retention in the fabric and mechanical leakages should be negligible in a well-maintained and properly operated machine. In tests conducted by an F-113 machine manufacturer, it was found that 10 to 12 g of solvent were retained in a 12 lb load of clothes.[21] This corresponds to approximately 0.002 lb of solvent per pound of clothes, or about 5% of the total solvent loss.

The filter cartridges are normally replaced after approximately 1,000 to 2,000 lb of cleaning; a discarded cartridge contains about 3.5 to 5 lb of solvent.[6,21] In some machines a portion of this solvent can be recovered by placing the used cartridge in the cleaning drum and running the unit through the drying cycle without the drum turning. A part of the solvent will evaporate and be recovered.[5] No data were found for actual quantities of solvent retained in the filter cartridges on a single cleaning-drying cycle basis, or for the recovery of solvent using the drying cycle technique. This filter device may be responsible for a considerable portion of the solvent "consumption" in each cleaning-drying cycle.

Oil sludge from the distillation system is normally collected after about 1,000 to 2,000 lb of cleaning. The total accumulation after this quantity of cleaning is approximately 0.5 to 1.0 gal. of which about 5 to 10% is solvent.[6,21] Using an oil sludge density of 6.5 lb/gal. and a 10% solvent content, an average solvent content per pound of clothes cleaned would be about 3×10^{-3} lb or approximately 8% of the total solvent consumption per cleaning-drying cycle.

Potential Emission Control Techniques

F-113 dry cleaning machines must be well-designed and constructed units with a minimum of solvent loss in order to remain competitive with the other lower-priced solvents. A conclusion from the TRW study was that with good operating and maintenance procedures, a 5 to 6% reduction in F-113 solvent consumption would be the maximum that can be attained. These operating and maintenance procedures would include strict adherence to the manufacturer's suggested maintenance program, as well as a record-keeping system for solvent consumption and cleaning production. The annualized costs for these procedures were considered to be negligible. No other emission controls were recommended for F-113 machines.[5]

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APPENDIX

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